Application-side merit-order-curves for synthetic fuels in the German energy system

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Abstract

German energy and climate policy scenarios assume that by 2050 the use of synthetic fuels will increase massively with growing climate protection ambition level. In the scenarios, synthetic fuels are also used in applications where, from today's perspective, electrification would also be possible in 2050. So synthetic fuels are also employed in areas for which adequate renewable alternatives to fuel utilization are available. A model-based static analysis is used to create application-side merit-order curves that compare synthetic fuels with conventional fossil as well as electrified applications. This will provide an initial assessment of the actual cost-efficient uses of synthetic fuels.

The analysis shows that considering current energy price trends for the time horizon of 2050, synthetic fuels are not an economic feasible option, compared to conventional fossil fuels. However, combining synthetic fuels with high efficient technologies like fuel cells offers cost advantages over the conventional fossil alternatives. This can be observed particularly in parts of the transport sector, where synthetic fuels could contribute to a cost-optimal defossilization strategy. However, additional costs of overall 48 billion (bill.) € arise due to the use of synthetic fuels compared to the conventional alternative. These additional costs are only about twice the German 'EEG Umlage' in 2018. If synthetic fuels and electrification are compared in terms of defossilization[1], it becomes clear that there are areas where synthetic fuels are preferable to electrification from a cost point of view. Particularly in the transport sector, there are synfuel-based applications that can be used cost-effecient for the defossilization of the energy system. In addition, the literature review shows that nearly 28% of applications exist where no technologically mature and efficient electrification option to defossilize the energy system could be identified. In the transport sector, in particular, there are synfuel-based applications that can be cost-efficiently used to defossilize the energy system. The cost-quantifiable applications result in overall additional costs of 22 bill. € for synfuel utilization compared to the electrification.

1 Motivation

The analysis of energy and climate policy scenarios shows that a massive use of synthetic fuels is expected by the year 2050 in case of a high climate protection ambition level [1], [2], [3], [4], [5]. The mere electrification and implementation of incremental efficiency and sufficiency measures is not enough to achieve ambitious climate targets [6], [7]. In addition, the share of short-term and seasonal fluctuating energy will continue to grow in the wake of the Paris Climate Agreement and the implementation-oriented decisions of Katowice. Temporarily, this can lead to considerable residual loads in the energy system, in times of high demand and low feed-in from renewable energy sources [8], [7], [9], [10]. Besides the greenhouse gas (GHG) emission reduction, the use of synthetic fuels (synfuels) offers short-term and long-term flexibility in the energy system as well as the use of existing infrastructure and trading networks [11], [12], [13], [14], [7]. However, in this context, the use of synthetic fuels risks causing inefficiencies in the energy system as they could be used, although cheaper and more efficient alternatives measures to reduce GHG-emissions are available. Moreover, if the synthetic fuel demand is not completely covered in Germany, the energy dependence on one energy source abroad shifts to the next. Due to a lack of alternatives the use of synthetic fuels is expected mainly in the transport and industry sector [1], [15]. In the transport sector, this is particularly true for applications that are difficult or from today's perspective technologically impossible to electrify, such as road freight transport, shipping and air transport. The focus in the industry is on applications in the industry branches *iron and steel* and *basic chemicals*, in which electrification proves costly or technically challenging and fossil energy carriers are used as feedstock [16], [17].

Currently reported GHG-reduction cost-curves do not focus on the utilization of synthetic fuels [3] and if so, the granularity of synfuel measure is low. Since synfuels deployment is often not the most efficient option for defossilizing the energy system,

[1] Used instead of decarbonation, because decarbonisation would preclude the use of carbonaceous electricity-based fuels

renewable alternative measures must be included in the decision-making process. By considering the opportuneness, it is highlighted which synfuel measures are necessary in which applications in terms of GHG reduction and which areas can already be defossilized more cost-efficient by electrification measures. Besides inefficiencies that can result from the choice of the GHG reduction measure in the individual applications, also the additional costs are to be determined, which result from the use of synthetic fuels in comparison to conventional fuels. In this way, the additional costs in the energy transition can be captured by using synthetic fuels compared to current conventional technologies [18].

2 Methodological Procedure

For the analysis of synthetic fuels utilization in the German energy system, cross-sectoral static merit-order-curves are compiled with a time horizon to 2050. Two investigation strategies are carried out: On the one hand, the synthetic fuel usage is compared with fossil fuel based applications in a merit-order. On the other hand, if possible, electric alternatives are identified and compared with the synthetic fuel input in a cost side differential-cost analysis. With a 100% renewable electricity mix, the comparison of synthetic fuels and electrification in both cases is expected to result in nearly complete reduction of GHG emissions in the energy system. The following analysis focuses on the private households, transport and industry sectors, without considering the use of synthetic fuels in the power sector. This is mainly due to the fact that renewable energy sources are considered to be an economically feasible option for defossilization of the power sector, assuming that the required flexibility in the energy system can be provided from the consumer side, e.g. industrial flexibility or vehicle-to-grid.

The methodological approach can be divided into five parts as shown in Figure 2-1.

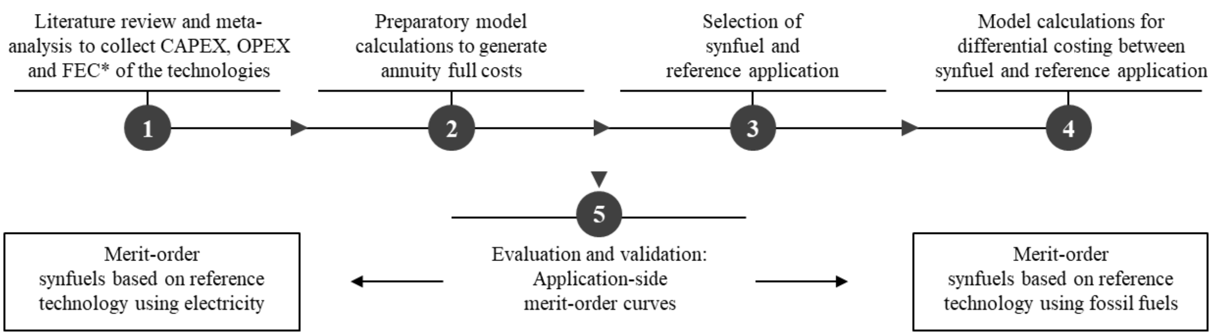


Figure 2-1: *Overview of the five main components of the methodological procedure*

In a first step the data required to create the cross-sectoral merit-order curves are collected via literature review and meta-analysis (1). In this way, synfuel and associated reference technologies are identified and their capital expenditure (CAPEX) and operational expenditure (OPEX) are recorded. In addition, the fossil final energy consumption of the reference technology is to be determined. The results of this literature analysis have already been published in advance in several publications and serve as input data in this consideration. In a second step (2) preparatory modeling work is carried out to calculate the annuity CAPEX and OPEX of the respective technologies by annuity method with time horizon of 2050. In the third methodological step, the respective substitution technology and the reference technology are selected, which are compared with each other. On the one hand, a conventional application using fossil fuels is employed, on the other hand an electrified application is used as a reference. In both cases, synthetic fuel application forms the substitution technology. In step (4), the required model calculations for differential costing between synfuel and reference application are performed. Finally, the results are evaluated, validated and transferred to merit-order curves via mekko-bar-charts (5).

2.1 Data collection via literature review and meta-analysis

In order to create application-side merit-order curves for synthetic fuels in the German energy system, a fundamental data research is required for technology and consumption parameters in the respective final energy sectors. This data research has not been conducted within this publication. For this purpose, the existing data of the sector models SopHa[2][19], TraM[3] [20] and SmInd[4] [18], [21] are used. Required full costs differentiated according to investment and fixed operating cost, energy consumption as well as other specific parameters of the sectoral applications and their developments until 2050 are available in the sector-specific data. The collected CAPEX include investment costs in new as well as the retrofitting of existing

[2] Sector Model Private Households
[3] Transport Model
[4] Sector Model Industry

equipment. The energy consumption of the applications constituting the basis for the calculation of the OPEX, which depend mainly on the energy price. Therefore, current energy prices as well as their future development have to be established. The static energy prices are calculated through a bottom-up modeling approach of the power sector.

In the underlying scenario modelling the final energy sectors and the energy prices, no technological leaps are assumed, but rather a reference development without high climate protection ambitions. System dynamic effects are not included in the analysis. This means that the changing market demand for synthetic energy sources does not entail an increase in electricity procurement costs or in higher costs for synthetic fuels themselves. In addition, there is no optimization of the power sector. System repercussions such as related expansion of infrastructure are not included in the analysis. Additional revenues through short- and long-term flexibility and security of supply are also not part of the analysis. If no additional investment costs arise from using synthetic fuels in existing applications, resulting differential costs does only consists of OPEX. For some applications learning curves are considered to establish the CAPEX development. When it is difficult to estimate a change in the application-related investment costs and moreover, only small effects on the costs are expected, learning curves are neglected [22], [22].

2.2 Preparatory model calculations in order to generate annuity full costs

As a basis for technology development, model calculations of the individual sectors with a time horizon of 2050 are required. The sector models, SopHa [19], TraM /[20] / and SmInd [18], [21] are used for this purpose. The sector models provide the basic investment and fixed operating costs as well as energy consumption and sector-specific parameters of the technologies. In all comparisons full costs of the applications are used to create the synfuel merit-order.

In order to create the application-side merit-order, the annuity full costs, which consist of investments and fixed operating costs, are used for the CAPEX calculation. The annuity of CAPEX is calculated by annuity method as follows (equation (2-1)):

$$a = C_o \cdot af_{\mathrm{n,i}} = C_0 \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \tag{2-1}$$

a	[€/a]:	annuity	n	[a]:	lifetime of technology
C_0	[€]:	initial investment/fixed operative costs	i	[%/100]:	interest rate
af	[1/a]:	annuity factor			

In order to calculate the OPEX, in addition to the variable operating costs and the energy consumption of the technologies, energy prices are required. These are estimated through a separate modeling process also with a time horizon of 2050 (see 3.1). The differential OPEX arises mainly from the difference in energy prices and energy efficiency of the synfuel application compared to the fossil or electrified alternative.

2.3 Selection of synfuel and reference technology

To generate the application-side merit-order curves, it is first necessary to outline comparable technologies. Applications that are already electrified or using renewable energy sources are not included in this analyses scope. Three different analysis are carried out, which are clearly summarized in Table 2-1.

Table 2-1: *Overview of the three analyzed cases*

	Energy carrier of substitution application	**Energy carrier of reference application**	**Characteristics of the analysis**
Case 1	Synfuel	Conventional fossil fuel	without technology change (TC)
Case 2	Synfuel	Conventional fossil fuel	with TC; using efficient synfuel technology
Case 3	Synfuel	Electricity	with TC; efficient synfuel is compared to electrifiable application based on the FEC related to conventional application

First of all, conventional fossil fuel applications are compared to synfuel applications. In this case using of synfuels does not require any technology change (Case 1). For example, in the transport sector, conventional fossil gasoline is replaced by electricity-based liquid gasoline. This approach applies analogously to other frequently used energy carriers like diesel, natural gas, kerosene and oil. In private households as well as in the transport sector, using synfuel is possible for almost all applications, without the necessity of further technology changes. In contrast, only gas consumption above 500 °C according to the temperature distribution in [23] is employed for industrial applications. This can be explained through the following two reasons: On the one hand, the use of synthetic fuels expected to be crucial for the defossilization of high temperature industrial processes to supply heat, due to the lack of efficient electrification options. This also applies to the further cases below. On the other hand, the utilization of synthetic fuels requires a technology change in the industry sector due to the heterogeneity of most industrial processes. In this first form of the application-side merit-order curve, however, only applications without technology changes are analyzed.

In the second case, conventional fossil and synfuel applications are compared as well (Case 2). However in contrast to case one, synfuels are applied for technologies that allow higher efficiency. For this purpose synthetic fuels are applied for a more efficient available technology option. For example, the fuel cell is used instead of conventional otto or diesel engines in the transport sector. Another example is the replacement of oil boilers with more efficient gas boilers powered by synthetic methane instead of natural gas in the private household sector. In addition, this consideration includes the steel, cement and lime industrial processes. However, choosing a more efficient technology compared to Case 1 is, e.g. due to the lack of input data, not possible in every application. In order to include the complete energy consumption of the investigated final energy sectors, no technology change is carried out for the related sector-specific applications. Instead the electricity-based variant of the conventional energy carrier with the origin technology is used. For instance, similarly to the first case, electricity-based kerosene is employed in aircraft turbines instead of fossil kerosene.

In the third case, synfuel applications are compared with electrification options. As a basis the final energy consumption of the comparable conventional application is employed (Case 3). Here, the previously selected more efficient synfuel technologies (Case 2), such as the fuel cell for applications in the transport sector, are retained. If this is not possible, a different SynFuel alternative is chosen. For example, this applies to motorcycles in the transport sector where fuel cell application is not available. Moreover, in some cases an electrified reference technology is not available at all. For instance, considering the air transport subsector, from technological point of view, there is no efficient way for applications' electrification, due to the long travel distances. Nevertheless, in order to consider the whole energy consumption in the application-side merit-order curve, the non-electrifable applications are added to the left margin of the merit-order without specifying their costs. In this third case, both paths also include transformation of the energy system (related to defossilization). If the difference between the electric alternative and the synfuel application is presented in a merit-order, under the given assumptions, it can be concluded that all measures below the abscissa can be used for a cost efficient defossilization of the energy system.

An increased use of biomass is also not part of the analysis, since the sustainable domestic biomass potential is already being used almost completely[5] [24], [25]. Water and CO_2, which are mainly needed as basic materials for the production of synthetic fuels, have no limiting effect [25]. The study also assumes that synthetic fuels are generated entirely with renewable energy.

2.4 Model calculations for creating application-side merit-order curves

If a synthetic fuel application is compared to its fossil or electric alternative, the cost components of the merit-order curves result from the difference between both application types. In mathematical terms, this can be expressed as follows (equation (2-2)):

$$\Delta costs_{\mathrm{app}} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{n}}(CAPEX_{\mathrm{syn,i}} - CAPEX_{\mathrm{ref,i}}) + \sum_{\mathrm{j=1}}^{\mathrm{k}}(OPEX_{\mathrm{syn,j}} - OPEX_{\mathrm{ref,j}})}{FEC_{\mathrm{conv,app}}} \tag{2-2}$$

Δcosts	[€/kWh]:	specific delta costs	app	[dl[6]]:	index application
CAPEX	[€]:	capital expenditure	OPEX	[€]:	operational expenditure
ref	[dl]:	index reference technology	syn	[dl]:	index synfuel technology
FEC	[kWh]:	final energy consumption	conv	[dl]:	index conventional

The resulting cost differences are combined across sectors for each five-year time cycle between 2020 and 2050. Subsequently, the differential costs are prioritized, using a descending order from the lowest to the highest application pair. For each pair, the final energy consumption of the comparable conventional application is taking as a basis. All modelling input parameters are summarized in the appendix, enabling a database for understanding and reproducing the modelling results, as well as

[5] Cross-sectoral shift would be possible, but is not included in this consideration
[6] dl: dimensionless

conducting further sensitivity analysis. Both, the specific conventional energy consumption per functional unit and the specific OPEX and CAPEX of the model calculations are presented.

2.5 Evaluation: application-side merit-order curves

In order to construct application-side merit-order curves, the calculated data is evaluated, checked for plausibility and finally validated. Subsequently, the modelling results are transferred to mekko-bar-charts.

In the first two cases, comparing synfuel and conventional applications, there are two possible results. Either the conventional one is cheaper compared to the synfuel application or vice versa (1 and 2). The results for Case 1 are represented for the year 2020 and 2050. On the one hand, this evaluation can be used to show decreasing synthetic fuel prices parallel to continuously rising fossil fuel ones'. On the other hand, it reflects an overall efficiency increase between 2020 and 2050, due to improvements regarding of resources, materials and energy efficiency. The results for Case 2, are shown in a merit order curve only for the year 2050.

In contrast, comparing electrification options with the use of synthetic fuels, three possible results can be distinguished: The electrified measures can defossilize the energy consumption more cost-efficient than synfuel measures or vice versa (1 and 2). In addition, the result may indicate the lack of alternative technologically mature electrification option for the application's defossilization (3). In the third case analogously to the second case, only one merit-order curve for the year 2050 is provided.

Since the study analyses up to 52 different applications, the classification of the applications in the merit-order curves is provided using the annotation methodology shown in Figure 2-2

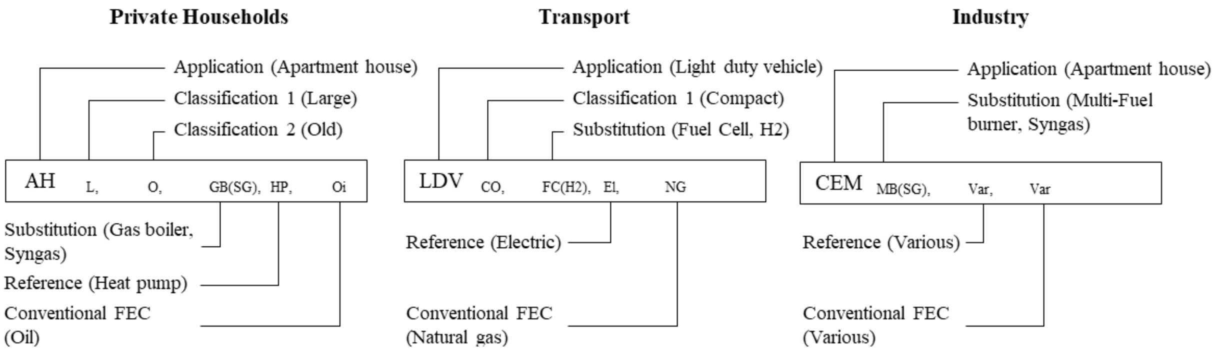


Figure 2-2: *Annotation methodology of application-side merit-order curve*

Each annotation include the abbreviation of the investigated application (e.g. AH: Apartment House), as well as up to two further classifications regarding the given application. For example, in the household sector apartment houses are differentiated in terms of their size and age class (Classification 1 and 2). In cases where a given application has only one (see Transport) or no further classification (see Industry), the missing abbreviations are not mentioned in the technology annotation at all. After the applications‘ classification, the substitution technology is abbreviated, together with the related to it energy source specified in brackets. For example, in the industrial sector various combustion technologies are being replaced by a multi-fuel burner, which allows the use of synthetic methane [26].

After the substitution technology, the reference technology is listed. For example, in the comparison of electrification and synfuels, electric drives (El) are compared with fuel cells (FC) in the transport sector. Finally, it is provided which conventional energy consumption is used to the comparison between substitution and reference application. For example, the comparision of electrification measures and synthetic fuels utilization for compact class light duty vehicles, is based on the fossil final energy consumption related to the usage of ‘natural gas’. A change in conventional energy consumption due to higher efficiency of one of the two technologies is not revealed in the static merit order.

3 Modeling parameters

This section explains the modelling input parameters for generating the application-side merit-order curves in the model.

3.1 Costs of energy carriers and CO_2

The operating costs of the applications are primarily determined by the energy prices. The energy prices are given in the unit €/MWh. Most of the values are either derived from external sources or based on own estimations as shown in Table 7-1 at the Appendix A. The costs for district heating, conventional electricity and conventional hydrogen are based on the BAU-scenario developed in the project Dynamis [27] and simulated in the linear optimization model ISAaR [28]. The synthetic fuel costs are calculated using a literature-based bottom-up levelized cost approach, providing investment, fixed and variable operating costs for each specific plant. The analysis consider an utilization rate of 4000 full load hours of the electrolyzes.The energy costs of carbon-based synthetic energy carriers are strongly dependent on the CO_2 supply price. For the synthetically produced energy carriers, a CO_2 price of 47 €/tCO_2 from industrial processes in 2050 is assumed. This results from an analysis of existing scenarios with Carbon Capture and Use as a GHG emission reduction option (CCU). The price for direct air capture is set to 390 €/tCO2 in 2020 and 220 €/tCO2 in 2050, based on results from analysis of existing modelling scenarios [29], [30]. It should be noted that with higher full load hours, prices for synthetic methane fall greatly.

Both, for the production of synthetic fuels and the direct use of electrical energy in electricity-based applications, energy prices are related to the use of 100% renewable energy sources (2020: 50.3 €/MWh, 2050: 39.5 €/MWh). The import of synthetic fuels is not permitted in the static analysis. Although electricity-based imported fuels offer lower energy prices compared to domestic fuels, they are also associated with extremely high uncertainties regarding the political situation and interest rates prevailing abroad [31].

3.2 Parameters of technologies in the different sectors

In this subsection, the examined technologies and applications from the household, transport and industrial sectors are presented and described. In order to calculate the annuity full costs for the merit-order construction, data of the FfE sector models SopHa (private households) [19], TraM (transport) [20] and SmInd (industry) /FfE-08 19/ are used. All relevant input parameters are summarized in Appendix B and Appendix C.

In the household sector, a distinction is made between building types and age classes. Four building types are to be distinguished. Detached houses are the smallest building type and have accordingly the lowest final heat consumption. In general, it can be observed that as the building size increases, so does the building's heat demand. Appartment houses are divided in further classes dependent on their size: small, medium and large. In addition, a distinction is made with regard to the building age class. Buildings constructed before 1995 are assigned to an ‘old buildings’ category and newly-constructed buildings respectively to a 'new buildings' category. The household applications considered in the course of the study are cover 66% (281 TWh) of the total conventional household fuel consumption in 2015 (429 TWh) [32]. If district heating, coal and lignite are not taken into account, as only oil and gas boilers are relevant for the analysis, the investigated technologies cover 75% (281 TWh) of the total household fuel consumption in 2015 (375 TWh) [32]. The input parameters with the greatest impact on the results in the private household sector are building size, specific investments, useful life and the heating system efficiency.The specific investments can be calculated with the nominal power of the heating systems, which in turn depends on the size of the building. At 30 years, the assumed useful life of fossil boilers is significantly higher than that of air source heat pumps. The main literature reference sources in this context are [33] for investments, [34] for useful life and [2] or [35] for efficiency. A detailed description regarding the modelling of this sector is provided in [19].

The transport sector include the widest range of investigated applications in this consideration. Therefore it requires a widespread, (detail) input data collection. Both transport modes - passenger and freight transport, are included in the sector analysis. Regarding the road traffic the analysis distinguished between light duty vehicles, motorcycles, service buses, coaches and commercial vehicles. Light duty and commercial vehicles are respectively classified based on their size. Rail transport is subdivided into passenger-, long-distance- as well as freight trains. In the air transport, it is distinguished between passenger and cargo planes, which are further divided into large and small planes. In water transport, only inland waterway is considered. In order to calculate the specific CAPEX and OPEX per kilometer, an additional distinction is made regarding the annual mileage of applications using different fuel types, such as gasoline, diesel and natural gas. This is done in respect to conventional, synfuel as well as electrical analysis, as the specific costs (€/km) are heavily dependent on the annual mileage of the particular application. The transport applications considered in the course of the study cover approximately 100% of the conventional fossil energy consumption in the sector in 2015 [36]. The most relevant input variables in this sector are the specific energy consumption per km and the investment costs of the respective technology. With regard to road transport technologies, it should be noted that a battery electric vehicle has a lower energy consumption than a comparable fuel cell electric vehicle. However, fuel cell electric vehicles have an advantage over the conventional application, regarding their efficiency rate. In addition, some substitution technologies have lower investment costs than the conventional application. A review of the transport sector modelling costs is presented in [20].

Due to the heterogeneity of the industrial sector and the associated inadequate data availability, only individual processes and temperature ranges, which are particularly suitable for the utilization of synthetic fuels, are considered. The research focus lies primarily on the production of steel, cement and lime. In addition, the gas consumption for the supply of process heat in a temperature range above 500 °C of various industry branches is combined. In this case, the replacement of conventional natural gas with synthetic methane is examined. Cost-efficient electrification is not be expected in this temperature range by today's state of technology to 2050. The analyzed applications cover about 67% (299 TWh) of the total industrial conventional fossil energy consumption (451 TWh) [37]. If only gas, oil and coal consumption is taken into account (excluding the use of district heating and other fuels), this percentage increase up to 78% (299 TWh of 384 TWh) [37].

Technical and financial input parameters for the industry sector are summarized in [26] und [38]. Modelling details for the industry sector can be retrieved from [18]. The results concerning the synfuels merit-order curves depicted in this paper are mainly influenced by the CAPEX variables technology lifetime and technology investment as well as factors influencing OPEX variables. The latter are mainly affected by the specific energy consumption, which is either stated in kWh per ton of product or derived from the process heat demand, the energy conversion efficiency as well as process specific full load hours. Depending on the modelled process the technology investment either reflects the greenfield investment in an alternative production rout (steel production) or adaptation to existing infrastructure which are a prerequisite for using synthetic fuels in the respective process (cement and lime production).

4 Results and Discussion

For each of the three analysis-cases described in subsection 2.3 a merit-order curve according to [22] is constructed, reflecting the comparision of synthetic fuels with conventional fossil- or electricity-powered applications. The results presented in Figure 4-1, are based on the assumption that synfuels are used in existing fossil applications, without any technology changes.

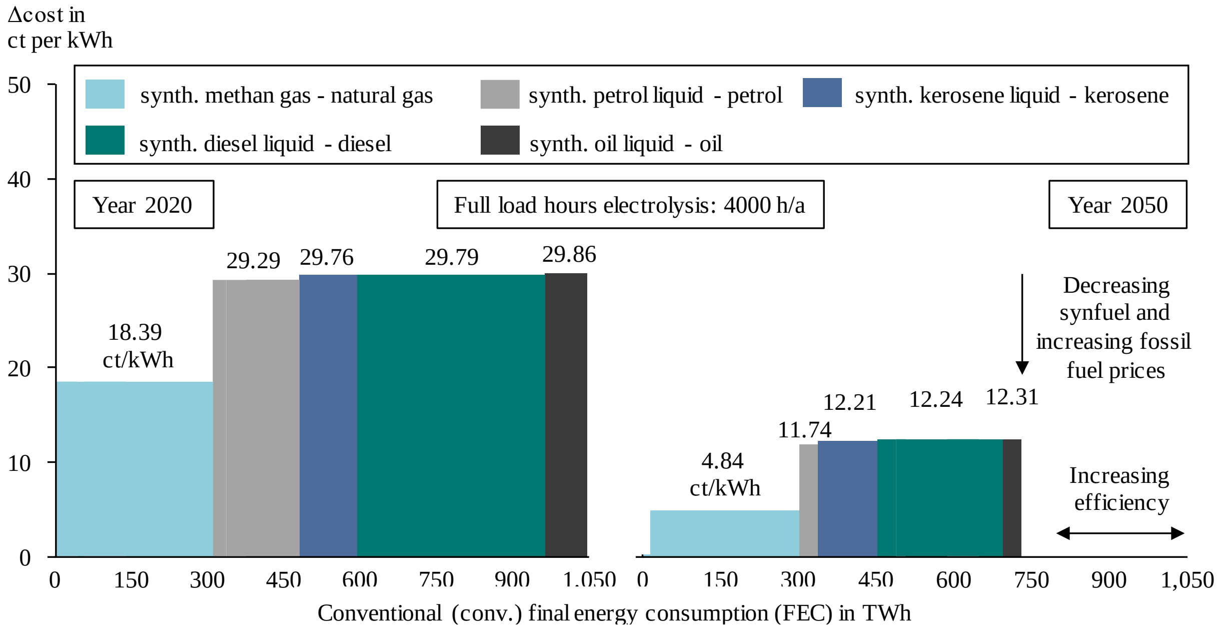


Figure 4-1: *Application-side merit-order of synfuels without a technology change in Germany 2020 and 2050 – Reference: conventional applications*

The resulting merit-order curve for 2020 is shown on the left side of Figure 4-1 and the one for year 2050, respectively on the right hand side of the figure. It turns out that if applications are compared based only on an energy carrier substitution without a technology change considering equal energy consumption and CAPEX for the reference and synfuels application, the resulting cost difference is not dependent on the particular application and sector, but only on the specific energy costs of the different energy sources. Consequently, without a technology change, it depends on the energy prices if cost parity between synthetic fuels and conventional fuels is achieved. Therefore, the price difference is determined solely by the energy price.

From this it can be concluded that the use of synthetic fuels for pure energy substitution causes equal costs for transport[7], household[8] and industrial[9] applications. Therefore, the same energy carriers can be summarized over the applications. Synthetic diesel is also used in different vehicle classes, where the unchanged energy consumption and investment costs of reference and substitution application determine only the energy price via the additional costs of the substitution. This also means that, as long as the cost of electricity is higher than the cost of fossil fuels, electricity-based fuels cannot achieve cost parity or even a cost advantage over conventional fossil fuels. However, application-side CO_2 pricing would allow a cost advantage for synthetic fuels from market participant's point of view, even at lower costs for conventional fuels.

If, for example, electricity-based synthetic gasoline replaces conventional one in the transport sector, there is no related technology change and therefore no change in energy consumption and CAPEX. The resulting differential costs between conventional and synthetic applications of 29.29 ct/kWh thus correspond only to the difference between the energy price of synthetic gasoline (34.42 ct/kWh) and conventional one (5.13 ct/kWh) in 2020. This consideration is valid for all other energy carrier pairs presented in Figure 4-1. By 2050 the differential costs get lower, as electricity-based fuel prices decrease considerably, due to falling electricity prices related to the usage of renewable energy sources.

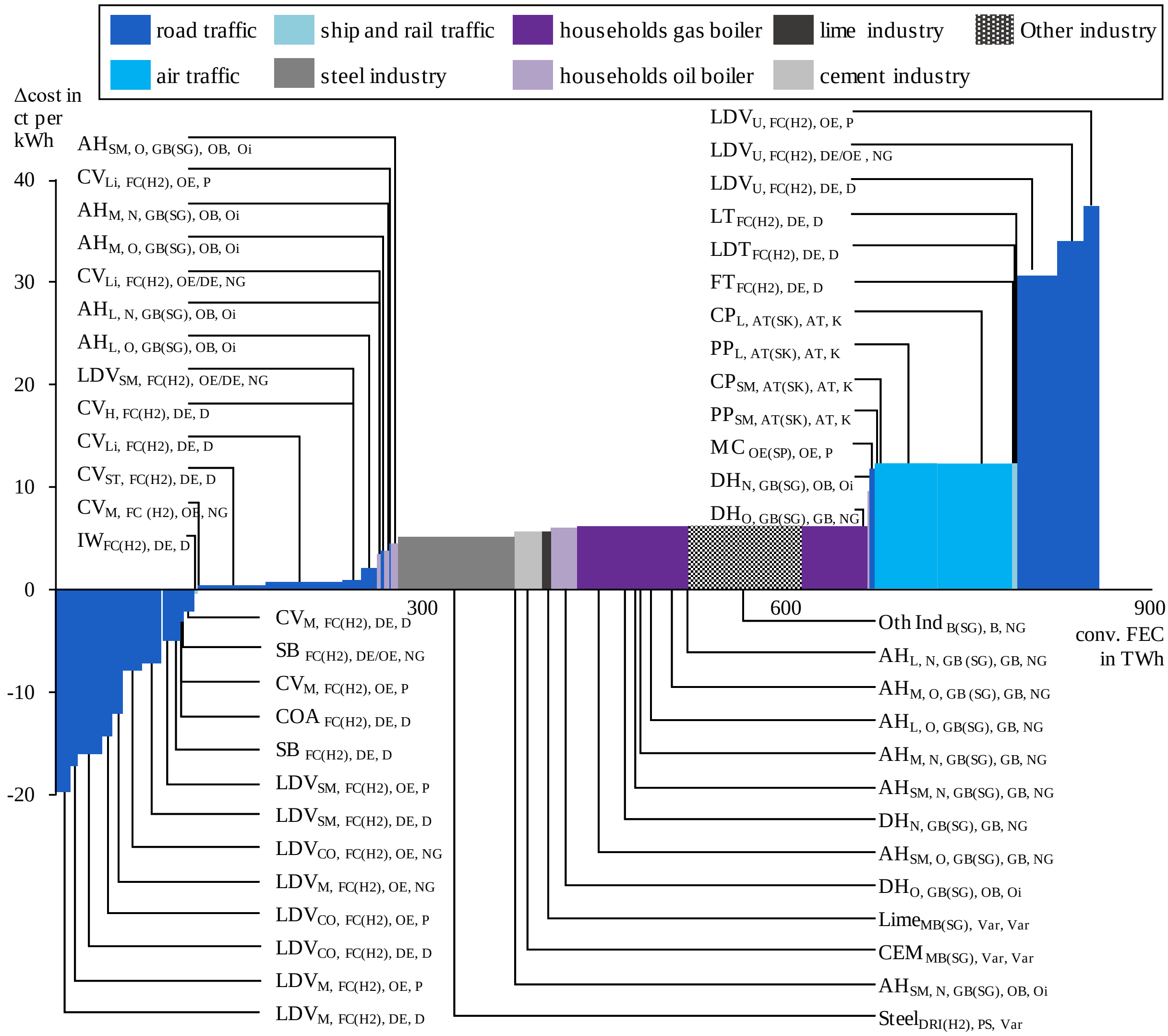
The conventional final energy consumption in 2050 is significantly reduced in most of the applications due to increased energy efficiency. It should be noted that with increasing capacity to produce synthetic fuels and economies of scale in the manufacturing of larger electrolyzers, further price reductions can be achieved. The energy costs for synthetic fuels dependent significantly on the the full load hours of the electrolyzer. In addition, imports of synthetic fuels are not permitted in these and the following considerations. If synthetic fuels are imported from regions with better renewable energy generation conditions than Germany, the price difference could be even lower [1], [31]. However, additional transport costs and poorer investment conditions, like higher interest rates and worse political conditions[10] could make synthetic fuel prices even more expensive.

If parallel to the energy carrier substitution, a technology change in some of the investigated applications is considered as well, the resulting efficiency and investments differences influence the application-side merit order curve. Figure 4-2 on the next page represents the results of the comparison between efficient synthetic- and conventional fuel-based applications. It turns out that in 2050 from a pure cost-efficient point of view, the usage of synfuels in particular applications is a more economical option to the fossil fuel alternative. This applied for applications, covering about 14% (17 TWh) of the total final energy consumption in 2050 (857 TWh). Only applications in the transport sector exceed the break-even point compared to conventional fossil fuels. In particular, some specific application of light duty vehicles powered by synthetic fuels are supposed to be much more economical than the conventional fuel alternative. This can be explained through the distinctly higher fuel cell efficiency, compared to conventional drive such as gasoline or diesel engine. Dispite their higher investments, hydrogen-based fuel cell electric vehicles could provide cost savings from up to 20 ct/kWh compared to conventional technologies. In contrast, the results based on upper class light duty vehicles comparison show that in this case the possible cost savings are affected due to increasing investments related to larger fuel cells and batteries. A nonlinear course of fuel cells and battery costs from small to larger drive systems can be observed. In the future, buses, commercial vehicles and inland waterways will also be able to operate partly cheaper with synthetic fuels as with conventional ones. In the air transport, conventional fossil-based kerosene is being replaced with electricity-based one, due to lack of available alternatives. Therefore, the higher energy prices for synthetic kerosene compared to the conventional one only influence the differential costs. As shown in Figure 4-1 this results in much higher costs (+12.21 ct/kWh) compared to the conventional application.

In contrast to the transport sector, where kinetic energy has a decisive effect on efficiency, the cost differential in the household sector is primarily determined by CAPEX. Therefore, even with the use of a more efficient gas boiler compared to the oil boiler, no cost parity with conventional fuels can be achieved by 2050. Gas boilers are fired with synthetic methane instead of conventional natural gas. Consequently, this application can become cost efficient only if the used synthetic methane is cheaper than the conventional natural gas, which is not assumed in the cost path (see Figure 4-1).

In addition to the higher synfuels prices, the required technology change enabling the synfuels utilization is related to some investment costs for the replacement of burners. The cost savings related to the slight efficiency improvement of modern burners is negligible compared to the higher additional CAPEX and OPEX. Cost parity with conventional fuels is not achieved in any of the examined industrial applications.

[7] Substitution of natural gas by synthetic methane in gas-powered vehicles
[8] Substitution of natural gas by synthetic methane in gas boilers
[9] Substitution of natural gas by synthetic methane in various burner
[10]depending on the region and import distance

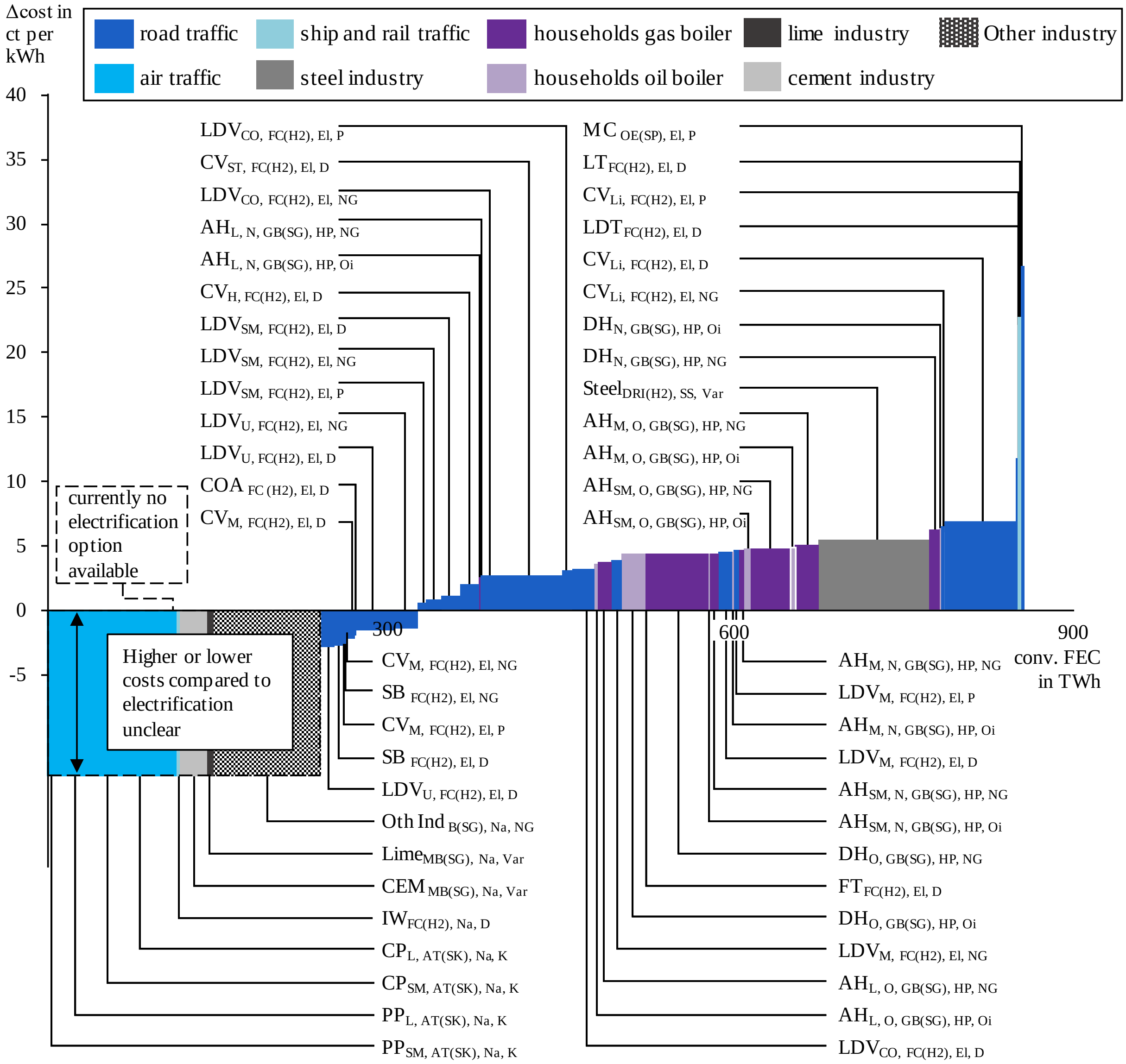


LDV:	Light duty vehicle	SM:	Small	OE:	Otto engine
SB:	Service Bus	CO:	Compact	DE:	Diesel engine
COA:	Coach	M:	Medium	SG:	Synthetic gas
CV:	Comercial Vehicle	U:	Upper	GB:	Gas boiler
IW:	Inland waterways	Li:	Light	Hyd:	Hydrogen
MC:	Motorcycle	H:	Heavy	SP:	Synthetic petrol
PP:	Passenger Plane	ST:	Semi-Trailor	SK:	Synthetic kerosene
CP:	Cargo Plane	L:	Large	NG:	Natural Gas
FT:	Freight train	DRI:	Direct reducted iron	Oi:	Oil
LDT:	Long distance train	Cem:	Cement industry	P:	Petrol
LT:	Local train	Lime:	Lime industry	K:	Kerosene
AH:	Apartment house	N:	New	D:	Diesel
DH:	Detached house	O:	Old	MB:	Multi-Fuel burner (B)
Oth Ind:	Other Industry	OB:	Oil boiler	Var:	Various energy carrier
PS:	Primary Steel	FC:	FuelCell hydrogen	AT:	Aircraft turbine

Figure 4-2: *Application-side merit-order of synfuels in Germany in 2050 - Reference: conventional fossil fuels and technologies*

The total additional costs compared to conventional technologies amount to about 48 bill. € in 2050, considering that all investigated applications are synfuel-based. For comparison: The German ‘EEG-Umlage’ in 2018 was over 25 bill € [39].

In the next step (Figure 4-3), each of the above investigated efficient synfuel applications are compared to their electric alternative, if such one is available.



LDV:	Light duty vehicle	SM:	Small	SG:	Synthetic gas
SB:	Service Bus	CO:	Compact	Hyd:	Hydrogen
COA:	Coach	M:	Medium	SP:	Synthetic petrol
CV:	Comercial Vehicle	U:	Upper	SK:	Synthetic kerosene
IW:	Inland waterways	Li:	Light	NG:	Natural Gas
MC:	Motorcycle	H:	Heavy	Oi:	Oil
PP:	Passenger Plane	ST:	Semi-Trailor	P:	Petrol
CP:	Cargo Plane	L:	Large	K:	Kerosene
FT:	Freight train	DRI:	Direct reducted iron (steel industry)	D:	Diesel
LDT:	Long distance train	Cem:	Cement industry	Var:	Various energy carrier
LT:	Local train	Lime:	Limeindustry	Na:	Not available
AH:	Apartment house	Oth Ind:	Other industry	SS:	Secondary Steel
DH:	Detached house	N:	New	MB:	Multi-Fuel burner (B)
GB:	Gas boiler	O:	Old		
AT:	Aircraft turbine	FC:	FuelCell hydrogen		

Figure 4-3: *Application-side merit-order of synfuels in Germany in 2050 - Reference: electric technologies and applications*

For nearly 28% (240 TWh) of the investigated applications (857 TWh), no comparable technologically mature and efficient electrification options could be identified. This relates to applications from the air and inland waterway transport, the lime and cement industry as well as other industrial processes related to gas consumption with temperature levels above 500 °C. Nevertheless, to take the energy consumptions of these applications into account, they are included in the merit-order with a fictitious price difference of 10 ct/kWh regarding the leftmost presented electrification option (upper-class light duty vehicles). Similarly, to Case 2, the results show that synthetic fuels are supposed to provide cost-efficient defossilization options, comparing to the electrification alternative, regarding some particular applications from the transport sector. Including non-electrifiable applications using synfuels, more than one third (325 TWh) of the applications are cost-efficiently defossilized by synfuel applications. However, if the non-electrifiable technologies are excluded, only 14% of the applications covering 85 TWh of the energy consumption have lower costs from system point of view, considering the usage of synfuels. This corresponds to a share of less than 10% of the total final energy consumption of all investigated applications in 2050. The resulting 14% are comparable to the values achieved by the results from Case 2 (see Figure 4-2). However, a causal connection is not revealed.

Examining the ranking of applications with synfuel and electrification option for defossilization of the final energy sectors in the merit-order, there are clear differences regarding the comparison of synfuels and conventional applications. For instance, in Case 3, upper class synfuel powered light duty vehicles are partly cheaper than the electrical option in this segment. This is mainly due to the notably higher investment costs for large battery storage units in vehicles. With hybridization through the additionally use of fuel cells in vehicles, significantly lower overall costs can be achieved. Therefore, upper class light duty vehicles with fuel cell provide a more cost-efficient defossilization option, compared to the electric alternative. This effect can also be observed in other road vehicles, like service busses and coaches, which require high driving ranges due to high annual mileage. Smaller and lighter all-electric light duty vehicles have lower overall costs from a system point of view, despite the related higher investments. This is due to their significantly lower operating costs per kilometer driven. The same applies to compact and medium class vehicles. It is astonishing that the electrification option is the more cost efficient alternative especially for large and heavy commercial vehicles. This is due to the fact that the slightly lower synfuel applications' CAPEX have less influence on the differential costs, compared to the high OPEX savings provided by the electrical option, related to the technology specific high annual millage. As expected, rail applications that are already electrified today provide much more cost-efficient option for defossilization compared to synfuels utilization in 2050. By motorcycles for which no fuel cell option is available, the high OPEX, resulting particularly from the usage of electricity-based liquid fuel influence the results. Therefore, the comparision of the synfuel options to its electrical alternative for this case results in the highest differential costs among all evaluated application.

In private households the heat pumps electrification is the more cost-efficient defossilization options compared to the synfuels alternative. This result is consistent with most energy and climate policy scenarios that see widespread use of heat pumps in the household sector [3], [40] [4]. According further energy and climate studies, synfuels are barely used in the houshold sector. In the low-temperature heat range, in addition to heat pumps, an electrode boiler is supposed to be an efficient electrification option, but this technology is not part of the evaluated technologies. In contrast to synfuels utilization, electrification measures could provide cost savings, particularly, in small detached houses. With increasing house size, the electrification cost advantage decreases disproportionately to the heat demand from a systemic perspective, due to higher investments for larger air heat pumps compared to gas boilers. Nevertheless, air heat pumps are still the more appropriate choice in this segment, due to their lower OPEX related to lower electricity price, compared to synthetic fuels ones.

There are almost no electrification options available in the industry for the investigated processes. Only the secondary steel production can be compared with the processes of direct reduction and melting in the electric arc furnace. The conventional energy consumption of primary steel production is the basis for the comparison. For the considered consumption in the cement and lime industry as well as the industrial gas consumption above 500 °C there is no technologically mature and efficient electrification option. If the direct reduction and the secondary steel production are compared, there are clearly cost advantages for the latter one. This is due to both, the lower CAPEX and OPEX of the secondary steel production. It should be noted, that a worldwide fully recycling-based steel production in 2050 is not a realistic scenario, due to the lack of scrap-resources availability [41]. Therefore, in order to fully defossilize the steel production, a direct reduction with hydrogen will be required in the steel industry.

The merit order provides heterogeneous results regarding the different analyzed sectors, although the applications from different sectors are lying within a closely range regarding their total specific costs. The cross-sectoral ranking may develop in a different way from the one provided here, as a result of sensitive changes. A sensitivity analysis is not part of the investigated research questions, but should be taken into account as an important aspect by conducting future works in this field. In total, if the examined applications switched to synfuels, the system costs will increase about 22 bill. € by 2050, compared to the fully electrical-based defossilization alternative.

This statement does not include the 240 TWh related to non-electrifiable applications according to the current point of view. Taking into account the assumed fictitious price difference of 10 ct/kWh between synfuels and the an electrifiable option the total cost difference decrease by 24 bill. €. Under this condition, in this thought experiment synfuels are evaluated overall as more economic feasible than electrification. Finally, it should be noted that the conventional energy consumption would decrease significantly, especially due to the electrification, but also through the use of synthetic fuels, related to higher efficiency rates compared to conventional applications

5 Conclusion

The application-side merit-order curves for synthetic fuels in the German energy system have shown from a cost point of view that areas exists, where synfuels compared to conventional fossil as well as electrifiable applications are preferable. The substitution of fossil with electricity-based fuels without a technology change has revealed that the cost-efficiency in this cases depends only on the energy prices. Compared to the year 2020, a significantly lower final energy consumption is expected in 2050, due to improvements in the applications efficiency. In addition, the differential cost gap between electricity-based synthetic and conventional fuels will become smaller. This results from the increasing fossil fuel costs, parallel to a falling electricity price tendency of renewable energy source, combined with economies of scale by the synfuel production. Nevertheless, without a technology change, none of the investigated synfuel applications could achieve a cost parity with the conventional option. This leads to the conclusion that as long as cost for electricity are higher than the one for fossil fuels, electricity-based synfuels will not provide a cost benefit from a system point of view.

In contrast, taking into consideration a technology change, about 14% of the investigated synfuels applications could provide a cost advantage compared to the conventional option. This is mainly due to the higher efficiency and consequently lower OPEX of the synfuels applications, which often compensate their higher CAPEX. The cost advantage of synfuels is evident particularly in the transport sector. Considering that all examined applications switch to synfuels, this will result in about 48 bill € additional cumulative costs compared to the conventional alternative.

In the last analyzed case, synfuel applications are compared with an electrical alternative. Based on renewable generated electricity, both options can provide almost fully defossilization. It is evident that for nearly 28% (240 TWh) of all investigated applications, there is no technologically mature and efficient electrification option available. In addition, a part of the applications covering about 85 TWh of the energy demand can be operated more cost efficiently with synthetic fuels, than with an all-electric options. However, it should be acknowledged that the utilization of synfuels, both in industry and transport sector requires a parallel partial electrification. This applies, for example, to fuel cell electric vehicles, where the vehicles dynamic motion requires a battery storage unit [42]. In the direct reduction of iron with hydrogen in the steel industry, a melting process in a near-fully electric-based electric arc furnace is required [43]. Analogous to Case 2, where synfuels are compared to conventional applications based on fossil fuels, the comparison between synfuels and electrification shows that the utilization of synthetic fuels offers a cost-efficient alternative, especially in the transport sector. The additional total costs are about 22 bill. € by the use of electricity-based fuels (non-electrifiable options excluded). Considering a cost difference of only 10 ct/kWh between synfuels and theoretically possible electrification options, a fully synthetic utilization is more cost efficient than the all-electric alternative. Whereas the overall statements provide an overview of the total costs range, the results show that each application has to be considered separately in order to achieve a cost-optimal defossilization from a system point of view.

However, it should be noted, that the conducted analysis is subject to strong uncertainties regarding the development of energy and technology costs. Although a sensitivity analysis in not being conducted, it becomes clear that small changes in energy costs can lead to significant differences in the cross-sectoral ranking up to a change in the sign of the differential costs.

Electricity infrastructure costs in the transport sector are not included in the analysis, but it is expected that these will shift the results toward more intensive synfuels utilization. However, it has to be considered that the development of a hydrogen infrastructure is also related to high investments. The construction of the already existing infrastructure has caused high investment costs in the past. This raises the question if the maintance of the already existing infrastructure, that limits the utilization of some high efficient applications if more cost efficient than the development of a new technology adequate one in the long term perspective. As the merit order provides a static ranking comparison, a changed demand of given energy carrier does not change its price. However, the price would be affected in a result of changing market demand, leading for instance to higher synfuel costs. Further research could expand the technology specter of this analysis, not only regarding further applications from the transport, household and industry sectors, but also including ones from the commerce, trade, service and power sector. The data provided in Appendix A, B and C can be used to carry out sensitivity analysis in future research.

The analysis shows that based on an appropriate technology selection, the utilization of synthetic fuels could provide a cost-efficient defossilization option from system point of view. It turns out that to avoid inefficiencies in the final energy sectors, application-specific solutions have to be developed, rather than relying on a homogenous defossilization pathway based for instance only on all-electric applications. The results indicate that, a mix of different application-specific synfuel and electrification options combined with a high acceptance for new technologies adoption are the crucial elements toward economic feasible defossilization of the energy system. The overall system cost-efficient defossilization is achieved more through a technology mix. A solution of one size fits all is not recommended due to the heterogeneity in the final energy sectors. Technology openness is the key to selecting the cost-optimal transformation path for defossilization of the energy system.

6 Literature

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7 Appendix

In the Appendix, the basic data to calculate the differential costs are available. The appendix is divided into three main components: the energy prices (1), the specific CAPEX and OPEX (2) and the specific conventional consumption of the applications (3).

Appendix A: Energy prices

Table 7-1: *Energy prices of the relevant energy carriers*

Energy carrier	Energy price [€/MWh] 2020	Energy price [€/MWh] 2050	Literature and origin
hard coal	8.4	9.8	[44] scenario B, [5]
lignite	5.9	5.6	[44] scenario B, [5]
natural gas	22.7	28.1	[44] scenario B, [5]
petrol	51.3	64.3	[45] & increase based on increase of oil price
diesel	46.3	59.3	[45] & increase based on growing oil price
kerosene	46.6	59.6	[46] & increase based on growing of oil price
Oil	40	53	[44] scenario B, no further increase after 2035
light oil	45.6	58.6	[45] & increase based on growing oil price
heavy oil	22.8	30.2	[47] & increase based on growing oil price
mineral oil	29.8	51.8	own estimation
biomass	27.6	26.3	own calculation
Coke	1.7	1.7	own estimation
converter & top gas	0	0	own estimation
other fuels	3.1	3.1	own estimation
district heating	19.4	34.6	based on simulation
electricity conventional	47.4	75.6	based on simulation
hydrogen conventional	23.6	28.1	based on simulation
liquid synthetic fuel through electrolysis (liquid diesel, petrol, kerosene)	344.2	181.7	calculation based on [48], [49], [50], [51] and further own assumptions
synthetic methane gas through CO_2	218.8	88.6	own calculation based on [14]
hydrogen through elctrolysis	146.3	63.6	own calculation based on [14]
electricity renewables	50.3	39.5	own calculation based on estimates of the future RES-mix in Germany

Appendix B: Specific CAPEX and OPEX for the different sectors, technologies and applications

The following section provides the specific CAPEX and OPEX for conventional, synfuel and electrified applications that serve as the basis for constructing the merit-order.

Appendix B.1: Conventional, fossil technologies/applications

Table 7-2: *Specific CAPEX and OPEX of selected technologies using conventional fossil fuels in the household sector*

Household sector			Specific CAPEX [€/bldg]		Specific OPEX [€/bldg]	
building type	building age	fossil fuel/application	2020	2050	2020	2050
detached house	≤ 1994	oil boiler	831	758	1 085	1 396
		gas boiler	1 554	1 499	533	660
	≥ 1995	oil boiler	690	784	706	877
		gas boiler	1 433	1 756	349	423
apartment house small	≤ 1994	oil boiler	1 166	1 058	2 144	2 741
		gas boiler	1 856	1 773	1 059	1 302
	≥ 1995	oil boiler	1 073	1 201	1 513	1 939
		gas boiler	1 772	1 992	748	925
apartment house middle	≤ 1994	oil boiler	1 631	1 479	3 616	4 568
		gas boiler	2 292	2 172	1 785	2 170
	≥ 1995	oil boiler	1 540	1 849	2 709	3 597
		gas boiler	2 205	2 498	1 339	1 686
apartment house large	≤ 1994	oil boiler	2 711	2 457	7 922	9 994
		gas boiler	3 378	3 171	3 911	4 749
	≥ 1995	oil boiler	2 657	2 984	5 568	7 159
		gas boiler	3 322	3 556	2 755	3 411

Table 7-3: *Specific CAPEX and OPEX of selected technologies using conventional fossil fuels in the transport sector*

Transport sector		Specific CAPEX [€/km]		Specific OPEX [€/km]	
modes of transport	fossil fuel/application	2020	2050	2020	2050
light duty vehicle small	petrol	0.214	0.207	0.026	0.027
	diesel	0.118	0.148	0.019	0.019
	gas	0.082	0.123	0.011	0.012
light duty vehicle compact	petrol	0.3	0.288	0.03	0.032
	diesel	0.166	0.209	0.023	0.023
	gas	0.13	0.194	0.013	0.013
light duty vehicle middle class	petrol	0.379	0.36	0.031	0.033
	diesel	0.213	0.265	0.025	0.025
	gas	0.173	0.254	0.013	0.014
light duty vehicle upper class	petrol	0.554	0.524	0.035	0.037
	diesel	0.265	0.33	0.031	0.031
	gas	0.213	0.314	0.015	0.016
motorcycle	petrol	0.192	0.201	0.021	0.024
service bus	diesel	0.98	0.983	0.21	0.27
	gas	1.068	1.045	0.104	0.133
coach	diesel	0.239	0.24	0.142	0.184
local train	diesel	2.143	2.184	0.372	0.476
long-distance train	diesel	1.157	1.157	0.172	0.22
passenger plane small	kerosene	2.677	2.677	2.011	1.902
passenger plane large	kerosene	7.024	7.024	3.286	3.109
light commercial vehicles	petrol	0.347	0.381	0.053	0.06
	diesel	0.203	0.229	0.06	0.064
	gas	0.19	0.199	0.028	0.029
medium commercial vehicles	petrol	0.261	0.248	0.099	0.113
	diesel	0.206	0.201	0.109	0.127
	gas	0.263	0.225	0.051	0.053
heavy commercial vehicles	diesel	0.37	0.368	0.156	0.152
semitrailer truck	diesel	0.325	0.355	0.202	0.198
freight train	diesel	52.433	58.208	8.484	10.866
cargo plane small	kerosene	2.677	2.677	2.011	1.902
cargo plane large	kerosene	7.024	7.024	3.286	3.109
inland waterways	diesel	6.167	6.167	3.251	4.164

Table 7-4: *Specific CAPEX and OPEX of selected technologies using conventional fossil fuels in the industry sector*

Industry sector	Specific CAPEX [€/t]		Specific OPEX [€/t]	
Production process	2020	2050	2020	2050
Steel production	133	133	37	41
Cement production	not specified	not specified	9	8
Lime production	not specified	not specified	15	15
Other Industry (gas consumption > 500 °C)	TOTEX			
Other industrial production processes	2020		2050	
Other industry	not specified		not specified	
Other industry without steel, cement and lime production	not specified		not specified	

Appendix B.2: Synfuel technologies/applications

Table 7-5: *Specific CAPEX and OPEX of selected technologies using synthetic fuels in the household sector*

Household sector			Specific CAPEX [€/bldg]		Specific OPEX [€/bldg]	
building type	building age	synthetic fuel/application	2020	2050	2020	2050
detached house	≤ 1994	oil boiler	831	758	8 194	4 329
		gas boiler	1 554	1 499	5 138	2 083
	≥ 1995	oil boiler	690	784	5 329	2 720
		gas boiler	1 433	1 756	3 364	1 334
apartment house small	≤ 1994	oil boiler	1 166	1 058	16 186	8 499
		gas boiler	1 856	1 773	10 203	4 108
	≥ 1995	oil boiler	1 073	1 201	11 425	6 014
		gas boiler	1 772	1 992	7 213	2 918
apartment house middle	≤ 1994	oil boiler	1 631	1 479	27 297	14 166
		gas boiler	2 292	2 172	17 203	6 845
	≥ 1995	oil boiler	1 540	1 849	20 447	11 155
		gas boiler	2 205	2 498	12 910	5 318
apartment house large	≤ 1994	oil boiler	2 711	2 457	59 801	30 992
		gas boiler	3 378	3 171	37 693	14 981
	≥ 1995	oil boiler	2 657	2 984	42 030	22 201
		gas boiler	3 322	3 556	26 556	10 761

Table 7-6: *Specific CAPEX and OPEX of selected technologies using synthetic fuels in the transport sector*

Transport sector		Specific CAPEX [€/km]		Specific OPEX [€/km]	
mode of transport	synthetic fuel[11]/application	2020	2050	2020	2050
light duty vehicle small	synthetic petrol	0.207	0.207	0.026	0.027
	synthetic diesel	0.148	0.148	0.019	0.019
	synthetic gas	0.123	0.123	0.011	0.012
	hydrogen (fuel cell) | petrol	0.304	0.204	0.028	0.009
	hydrogen (fuel cell) | diesel	0.155	0.135	0.028	0.009
	hydrogen (fuel cell) | gas	0.13	0.135	0.028	0.009
light duty vehicle compact	synthetic petrol	0.3	0.288	0.03	0.032
	synthetic diesel	0.166	0.209	0.023	0.023
	synthetic gas	0.13	0.194	0.013	0.013
	hydrogen (fuel cell) | petrol	0.383	0.236	0.043	0.013
	hydrogen (fuel cell) | diesel	0.196	0.156	0.043	0.013
	hydrogen (fuel cell) | gas	0.164	0.156	0.043	0.013
light duty vehicle middle class	synthetic petrol	0.379	0.36	0.031	0.033
	synthetic diesel	0.213	0.265	0.025	0.025
	synthetic gas	0.173	0.254	0.013	0.014
	hydrogen (fuel cell) | petrol	0.466	0.289	0.05	0.016
	hydrogen (fuel cell) | diesel	0.238	0.192	0.05	0.016
	hydrogen (fuel cell) | gas	0.199	0.192	0.05	0.016
light duty vehicle upper class	synthetic petrol	0.554	0.524	0.035	0.037
	synthetic diesel	0.265	0.33	0.031	0.031
	synthetic gas	0.213	0.314	0.015	0.016
	hydrogen (fuel cell) | petrol	0.984	0.758	0.051	0.016
	hydrogen (fuel cell) | diesel	0.503	0.502	0.051	0.016
	hydrogen (fuel cell) | gas	0.42	0.502	0.051	0.016
motorcycle	synthetic petrol	0.192	0.201	0.021	0.024
service bus	synthetic diesel	0.98	0.983	0.21	0.27
	synthetic gas	1.068	1.045	0.104	0.133
	hydrogen (fuel cell) | petrol	1.46	0.986	0.086	0.038
	hydrogen (fuel cell) | gas	1.46	0.986	0.086	0.038
Coach	synthetic diesel	0.239	0.24	0.142	0.184
	hydrogen (fuel cell) | diesel	0.365	0.25	0.056	0.025
local train	synthetic diesel	2.143	2.184	0.372	0.476
long-distance train	synthetic diesel	1.157	1.157	0.172	0.22
passenger plane small	synthetic kerosene	2.677	2.677	2.011	1.902
passenger plane large	synthetic kerosene	7.024	7.024	3.286	3.109
light commercial vehicles	synthetic petrol	0.347	0.381	0.355	0.17
	synthetic diesel	0.203	0.229	0.447	0.195
	synthetic gas	0.19	0.199	0.267	0.091
	hydrogen (fuel cell) | petrol	0.677	0.454	0.076	0.027
	hydrogen (fuel cell) | diesel	0.397	0.273	0.076	0.027
	hydrogen (fuel cell) | gas	0.355	0.239	0.076	0.027
medium commercial vehicles	synthetic petrol	0.261	0.248	0.665	0.318
	synthetic diesel	0.206	0.201	0.812	0.39
	synthetic gas	0.263	0.225	0.492	0.168
	hydrogen (fuel cell) | petrol	0.535	0.226	0.158	0.056
	hydrogen (fuel cell) | diesel	0.535	0.226	0.158	0.056
	hydrogen (fuel cell) | gas	0.535	0.226	0.158	0.056
heavy commercial vehicles	synthetic diesel	0.37	0.368	1.157	0.466
	hydrogen (fuel cell) | diesel	1.121	0.431	0.28	0.11
semitrailer truck	synthetic diesel	0.325	0.355	1.505	0.607
	hydrogen (fuel cell) | diesel	1.375	0.424	0.365	0.143
freight train	synthetic diesel	52.433	58.208	63.076	33.298
cargo plane small	synthetic kerosene	2.677	2.677	14.853	5.8
cargo plane large	synthetic kerosene	7.024	7.024	24.272	9.478
inland waterways	synthetic diesel	6.167	6.167	24.17	12.759
	hydrogen (fuel cell) | diesel	6.908	5.707	9.796	4.258

[11] electricity-based fuels

Table 7-7: *Specific CAPEX and OPEX of selected technologies using synthetic fuels in the industry sector*

Industry sector	Specific CAPEX [€/t]		Specific OPEX [€/t]	
Production process using synfuels	2020	2050	2020	2050
Primary Steel production	153	153	610	269
Cement production	+ 106 €/t	+ 106 €/t	61	33
Lime production	not specified	not specified	185	80
Other Industry (gas consumption > 500 °C)	TOTEX			
Other industrial production processes using synfuels	2020		2050	
Other industry	not specified		not specified	
Other industry without steel, cement and lime production	not specified		not specified	

Appendix B.3: Electrified technologies/applications

Table 7-8: *Specific CAPEX and OPEX of selected technologies using electricity in the household sector*

Household sector			Specific CAPEX [€/bldg]		Specific OPEX [€/bldg]	
building type	building age	electricity/application	2020	2050	2020	2050
detached house	≤ 1994	air heat pump	2 643	2 298	369	263
	≥ 1995		2 220	1 992	227	160
apartment house small	≤ 1994	air heat pump	3 673	3 178	715	506
	≥ 1995		3 399	3 131	485	340
apartment house middle	≤ 1994	air heat pump	5 105	4 396	1 164	811
	≥ 1995		4 722	4 453	840	595
apartment house large	≤ 1994	air heat pump	12 064	10 334	2 505	1 733
	≥ 1995		11 576	10 255	1 687	1 127

Table 7-9: *Specific CAPEX and OPEX of selected technologies using electricity in the transport sector*

Transport sector		Specific CAPEX [€/km]		Specific OPEX [€/km]	
Application	electricity[12]/application	2020	2050	2020	2050
light duty vehicle small	electric | petrol	0.296	0.206	0.006	0.004
	electric | diesel	0.151	0.137	0.006	0.004
	electric | gas	0.126	0.137	0.006	0.004
light duty vehicle compact	electric | petrol	0.349	0.228	0.008	0.006
	electric | diesel	0.178	0.151	0.008	0.006
	electric | gas	0.149	0.151	0.008	0.006
light duty vehicle middle class	electric | petrol	0.409	0.274	0.01	0.007
	electric | diesel	0.209	0.182	0.01	0.007
	electric | gas	0.175	0.182	0.01	0.007
light duty vehicle upper class	electric | petrol	1.068	0.784	0.01	0.007
	electric | diesel	0.545	0.519	0.01	0.007
	electric | gas	0.456	0.519	0.01	0.007
motorcycle	electric | petrol	0.172	0.166	0.004	0.003
service bus	electric | diesel	1.24	1.123	0.034	0.027
	electric | gas	1.24	1.123	0.034	0.027
Coach	electric | diesel	0.35	0.316	0.025	0.02
local train	electric | diesel	1.679	1.679	0.18	0.141
long-distance train	electric | diesel	6.991	6.991	2.553	2.004
light commercial vehicles	electric | petrol	0.421	0.364	0.015	0.009
	electric | diesel	0.246	0.219	0.015	0.009
	electric | gas	0.221	0.191	0.015	0.009
medium commercial vehicles	electric | petrol	0.433	0.304	0.038	0.026
	electric | diesel	0.433	0.304	0.038	0.026
	electric | gas	0.433	0.304	0.038	0.026
heavy commercial vehicles	electric | diesel	0.71	0.454	0.053	0.038
semitrailer truck	electric | diesel	0.623	0.431	0.068	0.049
freight train	electric | diesel	80.891	80.891	3.484	2.734

Table 7-10: *Specific CAPEX and OPEX of selected technologies using electricity in the industry sector*

Industry sector	Specific CAPEX [€/t]		Specific OPEX [€/t]	
Production processes using electricity	2020	2050	2020	2050
Secondary steel production	137	137	28	22

[12] OPEX normalized to the annual mileage of the conventional FEC, e.g. petrol, diesel or gas

Appendix C: Specific conventional energy consumption for the different sectors, technologies and applications

Table 7-11: *Specific fossil final energy consumption of applications in the household sector*

Household sector			Specific consumption [MWh/bldg]		Number of buildings (bldg) [bldg]	
building type	building age	fossil fuel/application	2020	2050	2020	2050
detached house	≤ 1994	oil boiler	23.8	23.82	2 117 454	877 105
		gas boiler	23.48	23.5	2 999 186	2 347 690
	≥ 1995	oil boiler	15.48	14.97	162 294	85 778
		gas boiler	15.37	15.05	772 807	603 417
apartment house small	≤ 1994	oil boiler	47.02	46.77	297 448	128 224
		gas boiler	46.63	46.34	909 638	743 166
	≥ 1995	oil boiler	33.19	33.1	38 409	23 947
		gas boiler	32.97	32.92	225 642	214 776
apartment house middle	≤ 1994	oil boiler	79.3	77.95	114 949	49 486
		gas boiler	78.62	77.23	353 310	28 8239
	≥ 1995	oil boiler	59.4	61.38	12 945	8 150
		gas boiler	59.01	59.99	76 020	72 551
apartment house large	≤ 1994	oil boiler	173.72	170.55	27 634	11 884
		gas boiler	172.27	169.01	85 213	69 442
	≥ 1995	oil boiler	122.1	122.17	3 553	2 150
		gas boiler	121.37	121.4	20 866	19 519

Table 7-12. Specific fossil final energy consumption of applications in the transport sector

Transport sector		Specific consumption [kWh/km]		Annual cumulated mileage [Mio. km]	
mode of transport	fossil fuel/application	2020	2050	2020	2050
light duty vehicle small	petrol	0.51	0.43	69 861	16 991
	diesel	0.42	0.33	83 343	52 528
	gas	0.49	0.41	2 551	31 111
light duty vehicle compact	petrol	0.59	0.49	69 724	16 958
	diesel	0.51	0.4	83 180	52 425
	gas	0.57	0.48	2 546	31 050
light duty vehicle middle class	petrol	0.61	0.51	40 229	9 784
	diesel	0.54	0.42	47 993	30 248
	gas	0.59	0.5	1 469	17 915
light duty vehicle upper class	petrol	0.68	0.57	86 264	20 981
	diesel	0.66	0.51	102 912	64 862
	gas	0.66	0.56	3 150	38 416
motorcycle	petrol	0.41	0.38	18 013	8 802
service bus	diesel	4.53	4.56	2 736	1 586
	gas	4.6	4.72	100	590
coach	diesel	3.06	3.11	482	279
local train	diesel	8.03	8.03	386	374
long-distance train	diesel	3.71	3.71	36	36
passenger plane small	kerosene	43.15	31.92	138	145
passenger plane large	kerosene	70.51	52.16	898	912
light commercial vehicles	petrol	1.03	0.93	1 249	220
	diesel	1.3	1.07	51 508	58 848
	gas	1.22	1.03	984	3 435
medium commercial vehicles	petrol	1.93	1.75	6	6
	diesel	2.36	2.15	3 485	3 618
	gas	2.25	1.89	3	3
heavy commercial vehicles	diesel	3.36	2.56	5 821	6 042
semitrailer truck	diesel	4.37	3.34	19 418	16 821
freight train	diesel	183.24	183.24	6	6
cargo plane small	kerosene	43.15	31.92	7	13
cargo plane large	kerosene	70.51	52.16	627	1 168
inland waterways	diesel	70.21	70.21	45	47

Table 7-13: *Specific fossil final energy consumption of processes in the industry sector*

Industry sector	Specific consumption [kWh/t]		Production volume [thousand t]	
Production processes using fossil fuels	2020	2050	2020	2050
Primary Steel production	4 778.8	4 778.8	26 249	20 008
Cement production	796	796	31 104	28 916
Lime production	1 107	1 107	6 605	6 482
Other Industry (gas consumption > 500 °C)	Consumption [TWh]			
Other Production processes using fossil fuels	2020		2050	
Other industry	121.5		94	
Other industry without steel, cement and lime production	120.4		93.2	