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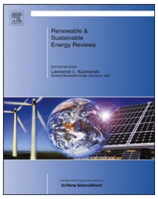

The future of transportation in sustainable energy systems: Opportunities and barriers in a clean energy transition

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ABSTRACT

Energy demand of a transport sector has constantly been increasing in the recent years, consuming one third of the total final energy demand in the European Union (EU) over the last decade. A transition of this sector towards sustainable one is facing many challenges in terms of suitable technology and energy resources. Especially challenging transition is envisaged for heavy-weight, long-range vehicles and airplanes. A detailed literature review was carried out in order to detect the current state of the research on clean transport sector, as well as to point out the gaps in the research. In order to calculate the resources needed for the transition towards completely renewable transport sector, four main alternatives to the current fossil fuel systems were assessed and their potential was quantified, i.e. biofuels, hydrogen, synthetic fuels (electrofuels) and electricity. Results showed that electric modes of transport have the largest benefits and should be the main aim of the transport transition. It was calculated that 72.3% of the transport energy demand on the EU level could be directly electrified by the technology existing today. For the remaining part of the transport sector a significant demand for energy resources exists, i.e. 3069 TWh of additional biomass was needed in the case of biofuels utilization scenario while 2775 TWh of electricity and 925 TWh of heat were needed in the case of renewable electrofuels produced using solid oxide electrolysis scenario.

1. Introduction

Transportation sector has proven to be one of the greatest challenges towards the sustainable development [1]. In the last decade, one third of the total final energy consumption and more than one fifth of greenhouse gas (GHG) emissions in the European Union (EU) have been a result of the fossil fuel-based transport sector [2]. Although the current trends in the heat and electricity sectors of some countries represent a significant progress in decreasing the demand and introducing more renewable energy sources (RES), the transportation still follows the old-fashioned trends of utilizing rising amount of fossil fuels. For example, Denmark has managed to reduce the heat and electricity demand over the past 30 years; however, energy demand in the transport sector has grown by almost 50% over the same period. Consequently, more energy is consumed in transport than in any other sector in Denmark [3].

Integrating electricity, heating and transport sectors enables higher penetration of renewable energy sources while battery electric vehicles (EVs), usage of more efficient forms of transport and introduction of alternative fuels can significantly decrease transport sector's dependence on fossil fuels. However, there is no simple unique solution when it comes to implementing RES and reducing CO_2 emissions in the transport sector [1]. Therefore, numerous studies deal with the various possible solutions for the future sustainable transport sector. Whereas some researchers focus on the transport sector as a whole, many studies analyse only a certain mode of transport, technological solution or a planning scheme applicable in one or more sectors. The latter claim is supported by the literature review presented in the following paragraphs of this section. The literature review starts with the overview of renewable research on light vehicles (cars), i.e. EVs, hybrid electric vehicles, biofuels and hydrogen driven vehicles. It is followed by the overview of research on other transportation modes such as heavy vehicles, aircraft and marine transport. Finally, a few research papers that focused on transport as a part of the whole energy system are presented and the research gaps are explored.

Common research topics within the transport area include EVs and the sustainable road transportation. Overview of the current models of electric cars and their features were analysed in [4], including the current technological status, business models, policies and the future development with the focus on the Danish and the Swedish context.

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Nomenclature

AC	Alternating current
BAU	Business as usual
BD_{demand}	biodiesel demand (TWh)
BET_{demand}	bioethanol demand (TWh)
$Biomass_{demand}$	final biomass demand needed to produce biofuels (TWh)
$BKER_{demand}$	biokerosene demand (TWh)
BEV	Battery electric vehicle
BTL	Biomass to liquid
CAPEX	Capital expenses
CEEP	Critical excess electricity production
CI	Compression ignition
CNG	Compressed natural gas
$CO_{2demand}$	CO_2 demand input for SOEC process, ton
D_{demand}	diesel demand (TWh)
DC	Direct current
DME	Dimethyl ether
DME_{demand}	DME demand (TWh)
EU	European Union
El_{demand}	electricity demand input for SOEC process (TWh)
EV	Electric vehicle
FCEB	Fuel cell electric bus
FCV	Fuel cell vehicles
FT	Fischer-Tropsch
GAS_{demand}	gasoline demand (TWh)
GHG	Greenhouse gas
HC	Hydrocarbons
$Heat_{demand}$	heat demand input for SOEC process (TWh)
HEV	Hybrid electric vehicle
HRES	Hybrid renewable energy system
IATA	International Air Transport Association
IC	Internal Combustion
ICT	Information and communication technology
IEA	International Energy Agency
IoT	Internet of Things
KER_{demand}	kerosene demand (TWh)
LCA	Life cycle assessment
LHV	Lower heating value
LHV_{BD}	lower heating value of biodiesel (GJ/ton)
LHV_{BET}	lower heating value of bioethanol (GJ/ton)
LHV_{BKER}	lower heating value of biokerosene (GJ/ton)
LHV_{D}	lower heating value of diesel (GJ/ton)
LHV_{DME}	lower heating value of DME (GJ/ton)
LHV_{GAS}	lower heating value of gasoline (GJ/ton)
LHV_{KER}	lower heating value of kerosene (GJ/ton)
LHV_{MET}	lower heating value of methanol (GJ/ton)
MET_{demand}	methanol demand
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
OPEX	Operating expenses
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
PV	Photovoltaic
RES	Renewable energy source
SEE	South East Europe
SEV	Small sized electric vehicle
SOEC	Solid oxide electrolysers cells
$Syngas_{demand}$	syngas demand for SOEC process (TWh)
USA	United States of America
V2G	Vehicle to grid
VOC	Volatile organic compound
η_{BTL}	total efficiency of BTL process (dimensionless)
η_{fer}	total efficiency of fermentation process (dimensionless)
η_{FT}	total efficiency of Fischer-Tropsch process (dimensionless)
η_{syn}	total efficiency of synthesis process (dimensionless)
η_{system}	total efficiency of electrolyser (dimensionless)

Among many findings presented, key technological advantages of electric cars, such as reduced CO_2 emissions, noise and air pollution were emphasized. On the other side, a battery was detected as the key challenge regarding its cost, range, safety and life expectancy. An overview of electric vehicles' technical characteristics, fuel economy, CO_2 emissions and charging mechanisms was carried out in [5], where the author covered three different types of EVs – hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and full electric vehicles (FEVs). The authors concluded that electric vehicles have better fuel economies compared to other types of vehicles; however, if electricity generated for recharging the batteries is produced from oil or coal-fired plants, CO_2 emissions can sometimes be higher compared to the conventional gasoline vehicles. In a similar manner, a comprehensive review of EVs and related technologies provided in [6], pointed out the need for further advancement of research in this area to lower the price and improve the technical performances of an EV battery. A review of charging optimisation techniques for PHEVs and EVs, conducted by Rahman et al. [7], concluded that the development of charging infrastructure is a crucial element for the future growth of electric transportation. Technological and policy aspects of implementing EVs in the Lithuanian context were analysed in [8]. Using a SWOT analysis (Strengths, Weaknesses, Opportunities, Threats), the authors found that the breakthrough impact on the local EVs market can be created by attracting companies investing in battery production plants or plants for power trains production. However, in order to achieve the latter, a need for an active engagement of the government was emphasized. Furthermore, the cost of a rapid transition to EVs was assessed in [9], using Australia as a case study. The latter study concluded that the transition to EVs can be achieved at approximately the same cost compared to the continued use of the conventional vehicles, if the battery costs fall rapidly and at about 25% larger cost if the battery costs remain high. In the heavy road transport sector, the development process and specifications of already existing heavy electric trucks were presented in [10]. The electric trucks are found to be useful for moving trailers in distribution centres, transport depots, container terminals and others. Developed electric trucks are quieter and require less maintenance than a diesel engine. Furthermore, Shafie-Khah et al. discussed the EVs in the electricity market context focusing on management schemes and vehicle-to-grid (V2G) technology, analysing the interplay between the transport sector and intermittent RES [11]. They argued that the spinning reserves and ancillary services markets will be the main targets of the EVs. They emphasized that in order to deal with uncertainties, such as the number of vehicles, price and time of charging, state of charge and driving patterns, stochastic techniques shall be used.

Expanding on these matters, integration of power and transport sectors was also a focus of many researchers. Christensen et al. [12] explored innovative business models to implement battery electric cars in Denmark, with the main emphasis on the interplay between electric vehicles and renewable energy generation. Their study concluded that some places, particularly Denmark, offer a great market and political setting to establish such business models in a successful way. A comprehensive review of research on the interaction between EVs and intermittent RES, carried out in [13], concluded that this kind of interaction is a very beneficial way to foster the development and implementation of both technologies. The study in [14] emphasized that incentive-based policies for V2G technology are essential for the successful implementation of the technology. An explorative study on synergies between EVs and photovoltaics (PVs) indicates that in the current distribution network of a medium size European city, EV penetration level is limited to only 18%, whereas in the smart grid framework, with a high level of PVs, that share can be increased by up to 64% [15]. Other authors showed that 50% penetration of EVs in the four biggest cites in Croatia, in a combination with PV penetration of 50% of electricity demand, could reduce the import of electricity for more than 4 TWh [16]. Hu et al. [17] stressed that the management of EV fleet is necessary to create better optimized charging profiles and that proper engagement of commercial actors and EV owners is crucial for establishing a sustainable road transportation system. The importance of fleet management charging has been discussed in [18–20] where dynamic programing optimisation results were compared withe results obtained by an existing heuristic charging algorithm used in EnergyPLAN software. The Authors have illustrated the advantages of the dynamic programming algorithm in minimizing the charging energy cost (35% to 50% reduction compared to the base case) and satisfying the aggregate battery charge sustaining conditions.

Focusing on other potential pathways for the future transport sector, such as biofuels and hydrogen, the authors in [21] assessed the environmental impact of various biofuels, including bioethanol, biodiesel and bio-hydrogen. They concluded that even with the amount of fossil fuels required for biomass farming and biofuel processing today, biofuels can still contribute in reducing the fossil fuel usage. A review of Fischer-Tropsch (FT) synthesis technology for biofuel production, made by Ali and Dasappa [22], showed that the FT synthesis from biomass is a promising technique for production of renewable fuels. The highest bio-oil productivity was derived from palm oil. On the other hand, they emphasized that the latter process is only sustainable if the waste land is used for cultivation. Cultivating waste land for biomass production was assessed in [23]. However, the authors showed that the cultivated biomass for the case of Croatia is not economically feasible. Anderson [24] investigated the effects of biofuels use on vehicle emissions. He found that GHG emissions may decrease even with increased utilization of fuels while air quality is expected to decrease with the increase in the use of biofuels. Furthermore, biofuels are detected as a possible pattern to mitigate the increasing energy demand in the Australian transport sector [25] while for the case of Thailand [26], biofuels showed better environmental performance than their fossil-based equivalents. On the other hand, the water demand for their production is significantly higher. Reviewing alternative fuels for compression ignition (CI) engines, Datta [27] found that although biodiesel application results in significantly better environmental aspects than conventional diesel, it deteriorates the performance of the engine. Potential of introducing hydrogen as an alternative fuel was investigated in the Malaysian [28] and Australian [29] context. In both studies hydrogen was assessed as technically feasible and for the Australian case, it was shown that hydrogen fuel cell and battery EVs can fully replace fossil fuel vehicles by 2050. Due to its low gravimetric density, the main problems of hydrogen are its storage and transportation [30]. In order to tackle the latter issue, many storage options of hydrogen have been investigated, such as compressed gas, cryogenic tanks, metal hydrides or carbon nanotubes [31]. The storage problem was also emphasized in [32], where a comprehensive review of recent developments in hydrogen production, application and storage was provided.

Connolly et al. [3] developed production pathways in the context of a renewable energy system for various fuels, with the aim to establish an overall comparison between those fuels. They emphasized that electric batteries are not suitable for all modes of transport and thus other, energy dense fuels are needed. Moreover, biofuels are likely to be unsustainable in the context of 100% renewable energy system so other forms of fuels need to be investigated as well. Following that approach, the authors in [33] analysed pathways for producing synthetic fuels with a special focus on solid oxide electrolysers cells (SOEC), combined with the recycling of CO_2. Synthetic fuel production was found to be beneficial for implementing high share of intermittent RES into an energy system, as it connects different sectors and makes the system more flexible. A conceptual design of an electricity-to-liquid fuel system made of SOEC stack working in co-electrolysis and a FT reactor was presented in [34], while the costs of synthetic fuel production using SOEC were assessed in [35,36]. It was found that pathways with higher share of biomass in the production process have the lowest costs; however they are not as flexible for wind integration as CO_2 recycling pathway. According to the authors in [37], a Power-To-Gas application by means of Renewable Hydrogen (H_2) production could be the viable solution due to its dual application: as a fuel for combustion or chemical conversion, as well as an energy storage medium for RES mismatch compensation. They found that when RES share ranges from 25% to 50%, using H_2 for heating purposes avoids the low round trip efficiency of its deferred electricity purpose. Eco-fuels production (different blends of hydrogen and natural gas) was found to represent a sustainable energy pathway on the local scale [38].

Many authors focused on technological solutions and planning schemes for other transport modes. A review of alternative fuels for the aviation sector, responsible for 2–3% of global anthropogenic CO_2 emissions [39], is provided in [40,41]. The authors in [42] examined the results from available measurements and proposed the first analytical approximation (ASAF) of the black carbon emissions reduction related with the usage of paraffinic alternative jet fuels. The conversion technologies for producing jet-fuels from biomass still need to undergo a considerable development to become economically feasible [35,36] while their competition with food production rises much awareness worldwide [44]. The study on prospects of biofuels in the Brazilian aviation sector [45] revealed that the high current demand of biodiesel for road vehicle fleet compromised the utilization of biofuels in other sectors, including the aviation. Furthermore, one possible economic route for the production of liquid fuels with high aromatics content, as an alternative to conventional bio-jet fuel production, was proposed in [46]. Another alternative for the aviation sector is solar powered aircraft system, a technology that is showing a potential to reach a major fraction of a future carbon-free energy portfolio in the aviation. However, it is necessary that the latter technology advances in order to overcome low conversion efficiency and high costs of currently available systems, with the energy storage being the key issue [47]. The most common used technologies for extracting and storing energy for solar-powered aircrafts today are silicon PVs and Li-ion batteries [48]. However, the authors argued that GaAs PVs and Li-S batteries are better suited for this use as the former technology is more efficient and the latter technology more energy dense [48].

Although limited in comparison to other sectors, different options have been analysed in the marine sector – namely fuel cell ships [49], supercapacitor ships [50] and different alternative liquid biofuels and synthetic fuels [43,44]. All the mentioned studies stressed the environmental benefits that the alternative solutions can bring, emphasized other strengths and barriers of those solutions and concluded that the serious research and development efforts are needed before they can become economically competitive. Furthermore, a well-to-tank analysis of various alternative fuels for Singapore's aviation and marine sector showed that the huge land use requirement for biofuels production will limit the availability of those fuels in Singapore [52]. Somewhat different solution for marine transport, a hybrid renewable energy system (HRES) for a ship, analysed in [53], proved to be a good alternative to reduce the GHG impact of the ship, implement new technological solutions in a conservative marine industry, achieve fuel savings and meet the new environmental policy regarding this sector.

Public transportation is also a common research topic within the field of sustainable transport. Hua et al. [54] concluded that technical targets for commercialization of fuel cell electric buses (FCEB) in North America and Europe have already been met. Moreover, the cost comparison between three different types of buses, i.e. diesel buses, compressed natural gas (CNG) and V2G electric buses was conducted in [55]. State of the art sustainable public transportation projects indicate that this sector has a great potential in this context. For example, in Gothenburg, a new electric bus nine kilometre-long route, served by three all-electric buses and seven electric hybrids, started to operate in June 2015 [56]. In China, around 16% of all city buses accounts for electric buses today, whereas 47,000 electric buses were sold only in 2014 and the first half of 2015 [57]. Moreover, Jaffery et al. [58] suggested a mass transit to solar powered railway transport system in Pakistan, in order to utilize country's huge potential for solar PVs and consequently reduce the fuel demand.

Some studies focused on modelling the future transportation sector taking a broad perspective; two scenarios utilizing electric vehicles and

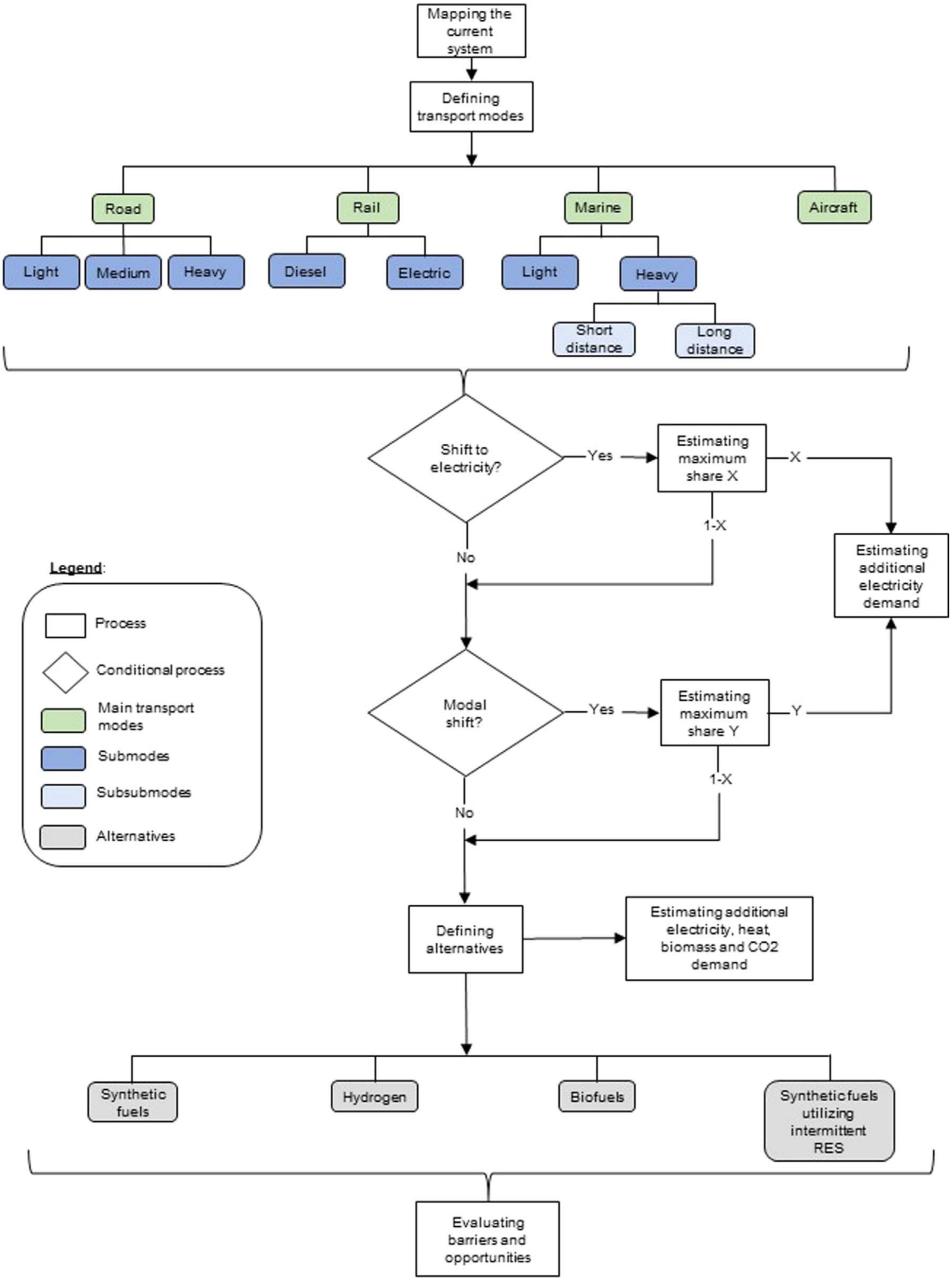

Fig. 1. Step-by-step process of estimating possibilities for transport sector transition.

hydrogen to high extent were presented for the case of Denmark [59], while four scenarios with different penetration of electric vehicles were analysed for the case of Sweden [60]. A fuel mix for the Indonesian road transportation sector for 2030, with 20% lower CO_2 emissions than the business as usual (BAU) scenario, was developed in [61] while energy efficiency potential in the transport sector for the case of Taiwan was assessed in [62]. Furthermore, the transport sector has been a part of models of 100% renewable energy systems in the EU [63] and the region of South East Europe (SEE) [64]. However, these studies have developed only superficial strategies about the transition of the transport sector, without detailed analysis of the limitations of each transportation mode.

As shown by the literature review, majority of the research papers and reports focused on battery electric vehicles, fuel cell vehicles and biofuels using conventional engines as the main alternatives to the currently existing transport sector, mainly driven by the fossil fuels. Moreover, they often focused on a specific transport sector, such as sectors of personal vehicles or marine transport. However, a lack of comprehensive research has been detected that would match the total additional energy demand for these cleaner alternatives with the scarce resources, as well as took into account the interaction between different transport modes. Additionally, still rising energy demand in the transport sector is contrasting the energy efficiency policies that are being promoted in the overall energy sector and thus, energy savings potential needs to be systematically assessed. Furthermore, as a variety of non-conventional alternatives are emerging, there is a rising need to review their current development status, calculate their potential and suggest new research areas that could be dealt with. Hence, this paper will expand the current state-of-the-art of by assessing the total resources needed for the main alternatives to fossil fuels in transport, on the scale of the EU, and by putting this demand into the perspective of the available scarce resources. A holistic approach has been taken into consideration in this paper, focusing on the interactions between different energy sectors and assessing different barriers and opportunities of the alternatives for penetrating the energy system on the more rapid scale. Utilizing a holistic approach, both energy savings potential and additional energy demand for cleaner fuels will be quantified on a system scale.

A proposed method for the shift of the transport sector towards sustainable one is presented in Section 2. Results, including the potential shift to electrified modes of transportation, alternative fuels production and the resource demand for it, are shown in Section 3. Sections dealing with the methods and results are followed by a discussion presented in Section 4 and an overview of the conclusions presented in Section 5.

2. Methods

Following the literature review presented in the introduction section, a method for the transition of the transportation sector towards 100% renewable one was developed. The clear focus of the method is to electrify the transportation sector as much as possible, i.e. the use of electricity as a primary energy input for the transport. Benefits of this transition are fourfold; first, a significant reduction in CO_2 emissions can be achieved if electricity is generated from cleaner energy sources compared to oil. Second, electrical engines are much more efficient compared to the internal combustion (IC) motors, which significantly increases energy savings in the system. Third, utilizing concepts such as V2G, in which the batteries of the vehicles can be used for storing the excess electricity generated and releasing the energy to the grid when there is a lack of supply, can integrate power and transport sectors, making the energy system robust and cheaper compared to the separately focusing on each of the energy sectors. Fourth, electric vehicles emit no emissions or harmful particulate matter from vehicles and thus, they do not contribute to the air pollution, an especially important issue in big, densely populated cities.

For the remaining part of the transportation sector, the part that cannot be directly electrified by the technologies existing today, several alternatives exist. Four of them are incorporated into the model developed in this paper. The developed model in a form of a logic tree is represented in Fig. 1 in detail.

Fig. 1 shows the process of modelling the transition of different modes of transport sector. The first step is the division of the transport sector into the main modes and further to lower level sub-modes where possible. In the latter step, the four main modes are identified, i.e. road, rail, marine and aircraft. The second step presents the evaluation of feasibility of the shift of fuel demand in each mode to electricity, followed by the estimation of the maximum possible share of the demand. A similar approach is used in the next step, in which the potential of a modal shift for the residual demand was assessed (residual demand is defined here as the demand after the maximum potential shift to electricity has been achieved). To clarify, the latter means that the part of the fuel demand in any transport mode that cannot be replaced by electricity, e.g. heavy road vehicles fuel consumption, can be shifted to another mode that has a higher electrification capability, e.g. electric railway. In the final step, alternatives are identified for the part that can neither be electrified directly, nor shifted to another electrified transport mode. In this stage, four alternatives were selected for the further quantitative evaluation, based on their technical and economic performances. For each of the alternatives, the main barriers, both technical and economic, as well as the main opportunities were analysed and presented in the following section.

After the estimation of the potential for the transition to electrical modes of transport had been performed and the alternatives for the residual demand determined, it was necessary to further elaborate additional alternatives for the remaining part of the transport sector. Therefore, three scenarios have been developed for meeting the residual demand by means of biomass, synthetic fuels and a combination of both. Before creating the scenarios, it was assumed that 57% of the residual fuel demand for passenger car vehicles was diesel (and the rest was gasoline), all the demand for medium vehicles, heavy vehicles and the marine sector was diesel and all the demand in the aircraft sector was kerosene. Assumptions according to the current trends in each sector are stated in [65].

In the *first scenario*, it has been assumed that all the diesel demand is replaced by biodiesel, gasoline by bioethanol and kerosene in the aircraft mode by biokerosene. Due to the differences in the chemical characteristics of fuels, a modified fuel demand was estimated using the lower heating value (LHV) of fuels, presented in Table 1. The calculation process is shown in (1), (2) and (3). In order to calculate the final biomass demand, process efficiencies showed in Table 2 were used. Efficiencies given in Table 2 present the total energy efficiency of the whole process – for the case of biofuels, from a raw biomass to the final product in a form of a liquid fuel. Furthermore, it was assumed that the 2nd generation biodiesel and biokerosene were produced by means of biomass to liquid (BTL) process and bioethanol through the fermentation process, as showed in (4). The final result obtained was the biomass (straw with 15% moisture content) demand needed to produce the estimated amount of biofuels.

Table 1
Lower heating value of different fuels [66].

Fuel	LHV [GJ/ton]
Methanol	19.9
Kerosene	44
Bio-diesel	37.8
Bio-ethanol	29.7
Gasoline	44.4
Diesel	43.4
Biokerosene	44
DME	31.7

Table 2
Total efficiencies of different processes used in the scenarios.

Process	Efficiency	Ref.
2nd gen. bioethanol fermentation	41%	[67]
2nd gen. biodiesel BTL	39%	[67]
2nd gen. biokerosene BTL	39%	[67]
Syngas synthesis methanol	67.3%	[66]
FT biodiesel & kerosene	51%	[66]
SOEC co-electrolysis	65%	[66]
SOEC assumed energy input distribution		
Heat	25%	[66]
Electricity	75%	[66]
CO_2 demand for SOEC	[t/GJ output]	
CO_2	0.105	[66]

$$BD_{demand} = D_{demand}*LHV_{D}/LHV_{BD} \tag{1}$$

BD_{demand} – biodiesel demand, TWh
D_{demand} – diesel demand, TWh
LHV_{D} – lower heating value of diesel, GJ/ton
LHV_{BD} – lower heating value of biodiesel, GJ/ton

$$BET_{demand} = GAS_{demand}*LHV_{GAS}/LHV_{BET} \tag{2}$$

BET_{demand} – bioethanol demand, TWh
GAS_{demand} – gasoline demand, TWh
LHV_{GAS} – lower heating value of gasoline, GJ/ton
LHV_{BET} – lower heating value of bioethanol, GJ/ton

$$BKER_{demand} = KER_{demand}*LHV_{KER}/LHV_{BKER} \tag{3}$$

$BKER_{demand}$ – biokerosene demand, TWh
KER_{demand} – kerosene demand. TWh
LHV_{KER} – lower heating value of kerosene, GJ/ton
LHV_{BKER} – lower heating value of biokerosene, GJ/ton

$$Biomass_{demand} = \frac{BD_{demand}}{\eta_{BTL}} + \frac{BET_{demand}}{\eta_{fer}} + \frac{BKER_{demand}}{\eta_{BTL}} \tag{4}$$

$Biomass_{demand}$ – final biomass demand needed to produce biofuels, TWh
η_{BTL} – total efficiency of BTL process, dimensionless
η_{fer} – total efficiency of fermentation process, dimensionless

In the *second scenario*, diesel was replaced by DME, gasoline by methanol and kerosene by biokerosene, the latter being the same as in the first scenario. Both synthetic diesel and methanol were assumed to be produced through the SOEC process. Firstly, the modified demand was calculated using the same method explained for the case of *scenario 1*, shown in (5) and (6) for DME and methanol, respectively. Next, the syngas demand was estimated using the assumption that the synthetic diesel was produced from syngas through the Fischer-Tropsch process, whereas methanol was a product of the syngas synthesis, explained in (7). Finally, electricity, heat and CO_2 demand needed to produce the estimated amount of syngas was calculated, showed in (8), (9) and (10) respectively. The biomass demand to produce the biokerosene was calculated, too.

$$DME_{demand} = D_{demand}*LHV_{D}/LHV_{DME} \tag{5}$$

DME_{demand} – DME demand, TWh
LHV_{DME} – lower heating value of DME, GJ/ton

$$MET_{demand} = GAS_{demand}*LHV_{GAS}/LHV_{MET} \tag{6}$$

MET_{demand} – methanol demand
LHV_{MET} – lower heating value of methanol, GJ/ton

$$Syngas_{demand} = \frac{DME_{demand}}{\eta_{FT}} + \frac{MET_{demand}}{\eta_{syn}} \tag{7}$$

$Syngas_{demand}$ – syngas demand for SOEC process, TWh
η_{FT} – total efficiency of Fischer-Tropsch process, dimensionless
η_{syn} – total efficiency of synthesis process, dimensionless

$$El_{demand} = Syngas_{demand}/\eta_{system}*75\% \tag{8}$$

$$Heat_{demand} = Syngas_{demand}/\eta_{system}*25\% \tag{9}$$

$$CO_{2demand} = Syngas_{demand}/\eta_{system}*0.105 \tag{10}$$

El_{demand} – electricity demand input for SOEC process, TWh
$Heat_{demand}$ – heat demand input for SOEC process, TWh
$CO_{2demand}$ – CO_2 demand input for SOEC process, ton
η_{system} – total efficiency of electrolyser, dimensionless

Lastly, in the *third scenario*, kerosene was also assumed to be produced by means of electrolysis. Synthetic kerosene production followed the same pathway as the synthetic diesel production explained earlier. This resulted in higher additional heat, electricity and CO_2 demand than in the *second scenario*. However, there was no additional biomass demand. This scenario was calculated according to the same method as explained in the *second scenario*, while only the synthetic kerosene demand was added in (7) which resulted in a higher syngas demand.

Nevertheless, evaluation of synthetic fuels production utilizing intermittent RES was carried out as a part of one of the alternatives. To do so, the EnergyPLAN model has been used [68]. The EnergyPLAN is a deterministic input/output model with the main purpose of analysing future energy systems. It is a simulation model, operating on an hourly time resolution. It has been already used to model numerous 100% renewable energy systems on various scales, from municipality [69] to the European level [70]. A detailed description of advantages and disadvantages of the model, as well as a brief comparison with other modelling tools, was given in [64].

3. Results

3.1. Mapping the current transportation modes and assessing the potential for clean transition

Following the method described in Fig. 1, the estimation of different transport means and their energy consumption was carried out. This was done using the Odyssee report [71] with the year 2013 taken as a base year. The share of different transportation modes can be seen in Fig. 2.

The final energy consumption of transportation sector in 2013 was 348.8 mtoe or 4056.5 TWh [72]. Further results of more detailed mapping of transportation modes can be seen in Table 3.

The more detailed division of the transport means is needed in order to be able to calculate the modal shift potential realistically, as well as to estimate the maximum possible transition to the electrified vehicles of the same type in a reasonable way (for example, IC cars to battery electric cars). Due to the serious constraints in finding the detailed enough literature dealing with the different types of ships and their respective shares in total energy consumption, marine mode of transportation was left out of the potential modal shift analysis. As it is consuming only 1% of the total final energy consumption in the transport sector, this simplification did not have a significant impact on the overall result. However, it is worth mentioning that a certain share of it could be electrified already today as stated in Table 4.

Table 4 presents possibilities of shifting transportation modes to

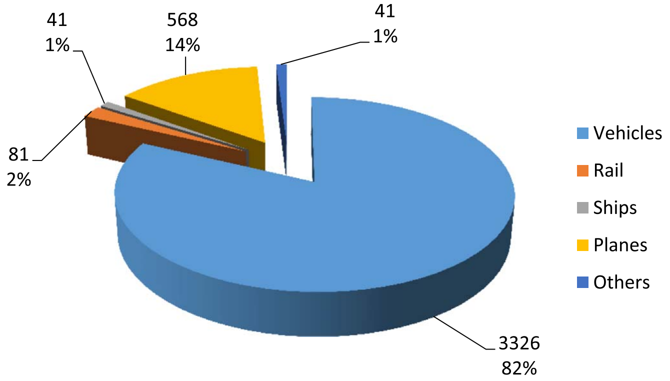

Fig. 2. A share and absolute values of the end use energy consumption for different transportation modes in the EU [TWh] [71].

Table 3
Mapping of share of different transportation means.

Transport mode	Transport sub-mode	Share of sub-mode in the transport mode	Ref.
Road	Light	59%	[71]
	Medium	23%	[71]
	Heavy	18%	[71]
Rail	Electric	80%	[73]
	Diesel	20%	[73]
Marine	No sub mode		
Aircraft	No sub mode		

electrified ones, as well as the modal shift potentials, that are possible already today, based on the references stated.

After taking into account all the measures presented in Table 4, it was calculated that the potential decrease in the demand for fossil fuels can reach a significant amount of 2931.3 TWh. Due to the shift to more efficient electrical modes of transport, the energy demand for the same amount of travel distance dropped from 2931.3 to 880.3 TWh, using efficiencies as defined in [68]. The remaining demand for fossil fuels of 1125 TWh cannot be directly electrified by the technologies available today and thus, alternatives need to be considered.

Alternatives that were assessed quantitatively by the authors are: synthetic fuels, hydrogen, biofuels and synthetic fuels utilizing excess electricity generation from intermittent renewable energy sources. Differences between synthetic fuels and synthetic fuels production utilizing excess electricity is that the latter assumes lower marginal prices of electricity that can be utilized, as well as increased possibility of integration of larger capacity of intermittent energy sources, creating additional demand for electricity that can be flexible. The choice of assessed alternatives is by no means statement that there are no other possibilities for the transition of the remaining part of the fossil fuel driven transportation sector; it is rather the choice for addressing the impact of highly discussed transition pathways in research community on a wider scale, including the real potential of renewable resources that are available for the transportation sector.

3.2. Results of scenarios

Using the scenarios developed and presented in the previous section, additional demand for alternative resources was estimated. Biomass scenario showed that for the production of biofuels for the remaining part of the transportation sector, which cannot be electrified today, there is a demand for 11,048 PJ or 3069 TWh of biomass.

In the scenario that considered production of synthetic fuels from the mix of biomass and heat and electricity utilized in electrolysers, the demand for biomass was calculated to be 1279 TWh, additional electricity and heat demand were estimated to be 1646 TWh and 549 TWh, while the CO_2 demand was 539.21 Mt. Thus, reduced biomass demand was complemented by increased demand for electricity and heat.

Table 4
Detected possibilities of shifting the transport modes to electrified ones.

Measure	Ref.	Discussion
Shift of 87% of passenger cars fuel demand to electricity	[73]	Technical potential based on the analysis of 3715 different vehicle profiles in the period of three weeks. It has been concluded that 87% of profiles can be fulfilled by battery electric vehicles (BEVs).
Shift of 70% of medium-heavy vehicles fuel demand to electricity	[4,74]	Electric vans have a proven range of up to 160 km, and from [4] it can be estimated that they can be used in 70% of the cases. Additionally, up to 10% of the vans can be replaced by small sized electric vehicles (SEV) [74].
Shift of 90% of heavy vehicles fuel demand to electricity (modal shift to electric rail transport)	[75,76]	TREMOVE model showed that 78% of the heavy duty truck transport emissions could be cut by modal shift to electrified trains [76]. In [75], an assessment of numerous different studies was carried out. Out of many other examples, TRANSCARE model estimated the potential of modal shifts of 5%, 40% and 100% on the distances of 50–150 km, 150–500 km and > 500 km, respectively. Furthermore, it is stated that for the case of Switzerland, the share of rail freight transport is equal to 66% already today. Based on studies presented, assuming the right policy measures and internalization of external pollution costs take place, up to 90% of heavy transportation vehicles could shift to electric rail transportation mode.
Shift of all the remaining diesel railway transportation to electricity	[59,77]	Adopted from the two scenarios in which the Danish railway sector is fully electrified in the year 2050 [59]. Furthermore, in [77] it was shown that the electrified trains share increased from 30% to 53% between 1990 and 2009 and from 53% to 80% until the year 2012. Hence, the total electrification of the railway system is possible already today.
Shift of 20% of light ships and 10% of heavy ships fuel demand to electricity	[51,78,79]	Diesel-electric ships could reduce the fuel demand by 30–50% [78]. Moreover, small ships powered by wind turbines and solar PVs, as well as fully electric battery ships are already in a commercial use [79]. However, less optimistic assumptions have been made to stay on the safe side, based on the fact that majority of the ships will still use liquid fuels in the future [51].
Modal shift 12.2% of aircraft sector demand to electric rail transport	[80–82]	In [39] and [40] it was shown that the short-distance flights can be challenged by high-speed trains. The reason is the long layover time atairports, as well as the travelling time to and from the airports which are usually located outside of the city. More specifically, in [80] for the case of Germany, it was shown that on distances of up to 500 km high speed railway is better option than airplanes. In [81], for different countries including Japan, France, England and others, it was shown that the majority of share on distances below 500 km are serviced by high-speed trains rather than planes. Based on [82], it was calculated that in terms of flown kilometres, the share of short distance flights (< 500 km) in Europe is 15.2%. Finally, it was assumed that 80% of these flights can be replaced by high-speed electrified trains.

Finally, the third scenario considered production of synthetic fuels solely from heat, electricity and CO_2. Although in this scenario there is no additional demand for biomass, there is a significant increase in demand for heat and electricity, calculated to be 925 TWh and 2775 TWh, respectively. Furthermore, demand for CO_2 in this scenario was calculated to be 908.98 Mt.

3.3. Detected barriers and opportunities for alternatives assessed

3.3.1. Synthetic fuels / Electrofuels

Following the terminology presented in [83], it is important to distinguish between the terms *synthetic fuels* and *electrofuels*. Whereas *synthetic fuels* refer to fuels produced from various fuels, including coal, gas or biomass through the FT process, the term *electrofuels* refers to the fuels based on the conversion of electricity to liquid fuel. Also, the production process of electrofuels does not include any fossil resource input; it is rather based on recycling CO_2 emissions and an electrolysis process powered by electricity. If both the carbon and the electricity are produced from RES, then the term *renewable electrofuels* can be used. On the other hand, the only renewable pathway of *synthetic fuels* production is biomass-to-liquid process. The fuels assessed in this paper are exclusively *electrofuels*, as their production process is based on SOEC co-electrolysis and syngas synthesis or FT synthesis. The following sections, however, include both *synthetic fuels* and *electrofuels*, as most studies usually do not make a clear distinction, or simply do not define the exact production process and thus, it is not possible to clearly define the exact term. On the positive side, the majority of the matter in this section – barriers and opportunities of synthetic and electrofuels - can be applied to both.

3.3.1.1. Economic barriers. Well to wheel energy efficiency from electricity for different synthetic fuels for the case of the Swedish transport sector was analysed in [84]. Authors analysed three different types of synthetic fuels to be used in IC engines, namely methane, methanol and FT-diesel, as well as hydrogen for fuel cell electric vehicles. Estimated well to wheel efficiency has been 25% for hydrogen and 14.3%, 13.5% and 12.6% for methane, methanol and FT-diesel, respectively. The same study estimated that for the case of the Swedish system, FT-diesel was competitive in the market only in the most optimistic scenario, whereas other investigated fuels had the potential to become competitive to fossil fuels and other renewable fuels especially. Hence, in order to increase the penetration of these types of fuels, either both the technology and running costs will need to go down, or the prices of fossil fuels would need to significantly rise in the future.

3.3.1.2. Technical (infrastructure & environmental) barriers. Authors in [85] emphasized the two main challenges the electrofuels are faced with when produced from renewable power. The first challenge is the fluctuation of the renewable energy sources, implicating low number of full load hours, which leads to the need of intermediate storage, fast response time of the electrolyser and high installed capacities. The second challenge is related to the possible high production costs due to the high electricity price, which may affect achieving the market price competitive level. Therefore, further electrolyser cost and efficiency improvements are necessary to reach the market entry level.

Analysing the atmospheric emissions from synthetic and electrofuels, they are heavily dependent on the resource input used for the production, as well as the production process itself. If produced through the biomass-to-liquid and FT synthesis (synthetic fuels), or CO_2-hydrogeneration using the renewable electricity and CO_2 from combusting biomass (electrofuels), then these fuels are considered carbon neutral, as every part of the production cycle is carbon neutral [83]. However, even in that case, often forgotten consequence of these fuels is the emission of CO, NO_x, benzene and particulate matter (PM).

Expanding on the matter of emissions, Ridjan [86] elaborated the environmental properties of the three main electrofuels – methanol, dimethyl ether (DME) and methane. In one of the biggest methanol consumers in China, the Shanxi province, CO, NOx and benzene emissions dropped by 20% and PM by 70% after introducing methanol in the transport system. Moreover, along with no CO_2, exhaust emissions from DME have no CO and NO_x, as well as no sulphur products. This makes DME the most beneficial alternative fuel from the emissions stand point. The study in [87] explored the NO_x emissions of alternative diesel fuels and found that FT diesel results in 21–22% lower NO_x emissions compared to the conventional diesel fuel. Somewhat different conclusion was made by authors in [88], who found that FT diesel caused higher NO_x emissions than the conventional ultra-low sulphur diesel, however PM emissions were found to be lower.

In order to increase the penetration of these types of fuels, either both the technology and running costs will need to go down, or the prices of fossil fuels would need to significantly rise in the future. On the other side, even if the technological and economic constraints will be successfully resolved, air pollution will still be an issue in the future. Somewhat contradicting research about emissions comparison of conventional and alternative diesel fuels show that more research needs to be carried out in this area.

3.3.1.3. Opportunities. As stated in [35], all synthetic fuel and electrofuels-related technologies are still in the R&D phase and therefore the costs of those technologies are very uncertain and can only be based on predictions and available stack costs. The study also concludes that they have higher production costs than the liquid fuels produced from biomass; however, synthetic fuel production pathways are more flexible in terms of wind power integration, which might be of high importance in the future energy systems.

Considering the engine design and the infrastructure, some synthetic fuels, like methane, require minor adaptions of the engine technology, while FT-diesel, for example, can be immediately used in the current systems [84]. This distinguishes them from, for example, biofuels that are currently available, as they require mixing with conventional fuels or a re-design of an engine. Furthermore, they can utilize already existing infrastructure built for fossil fuels, such as oil and gas pipelines, storages and charging stations. This makes them particularly interesting for urban areas, where larger infrastructure changes and actions might represent a challenge and cause inconvenience for the citizens.

This leads to the conclusion that the economy of synthetic and electrofuels highly depends on the future efforts in R&D, while regarding the infrastructure they are ready to be implemented into the existing system.

3.3.2. Hydrogen

3.3.2.1. Economic barriers. According to [89], today's global hydrogen market is currently valued at around $420–500 billion annually, with a 20% annual growth rate. It is however centred on the petrochemical industry where $107 billion p.a. is spent on production of hydrogen. Authors conclude that if the use of hydrogen is to be made widely available for merchant consumption, its production costs need to be reduced to become competitive. Another barrier is a high investment costs of the new infrastructure, as stated in [90,91] and explained into more details in the next paragraph.

Nowadays, the cheapest option for producing hydrogen is steam reforming of hydrocarbons. Utilizing the latter technology coupled with CO_2 sequestration could be an alternative if the “sustainable” routes prove to be too expensive in the future [92]. However, production of hydrogen in this way would curb the potential of power-to-gas technologies in balancing the power grid, seriously limiting the penetration of renewable energy sources.

3.3.2.2. Infrastructure barriers. Introducing the hydrogen driven fuel cell vehicles (FCV) into the transportation sector represents various technical and non-technical challenges. One of the main infrastructure challenges is building a suitable supply chain for automotive fuel cell parts, due to the fact that existing suppliers are usually not acquainted with the fuel cell technology or equipped to produce large amount of units at close to zero defect rates and low costs [90]. Authors in [91] stated that implementing FCVs requires a completely new fuelling infrastructure, as well as that currently hydrogen is supplied by specialized companies and not by the existing transport fuel industry. The latter is however seen as an opportunity to create new businesses and a chance for new players to enter the market. According to [93], hydrogen energy infrastructure development is often considered as an insurmountable technical and economic obstacle to the use of hydrogen as an energy carrier.

3.3.2.3. Benefits and opportunities

3.3.2.3.1. Air quality. Hydrogen is a clean fuel that generates no particulate or NOx emissions, which is very beneficial for the air quality, especially in congested cities. Downstream products of fuel cells are water and heat. The environmental impacts with other phases in the life cycle of a hydrogen system are similar to those for other energy technologies and may be small or large, mainly depending on the source of hydrogen [94]. If the electricity used in electrolysers was produced from renewables it can be concluded that no CO_2 emissions were generated in the whole process. Furthermore, even if the gas is used for electricity generation, CO_2 emissions would be produced from point source, which could be easier to deal with utilizing different technologies, as opposed to CO_2 emissions emitted in exhaust gases of moving vehicles.

Gasoline vehicles cause much higher ambient concentrations of pollutants compared to the FC vehicles. For the case of Sacramento, California, gasoline scenario produced 273 times greater CO, 88 times greater VOC, 8 times greater PM_{10} and 3.5 times greater NO_x concentrations compared to the hydrogen pathway [95]. The introduction of FC vehicles in the light duty vehicles in California was part of the research carried out in [96]. They have shown that significant reductions in ozone and $PM_{2.5}$ can be achieved in the year 2050, when FC vehicles market share reaches 50–100% market share.

3.3.2.3.2. Distributed production. Because of the low volumetric energy density of hydrogen, its distribution energy use is rather expensive and energy-intensive. Investment and pumping-power requirements are greater than for natural gas. Large-scale hydrogen distribution by pipeline adds \$1–2/GJ to hydrogen production costs. Distribution of liquid hydrogen is more costly (\$7–10/GJ) as energy is needed for liquefaction at −253 °C. Refuelling stations may add \$3–9/GJ to H_2 costs [97]. Hence, one suitable approach would be to produce hydrogen in on-site electrolysers, located in fuel stations or even in the home charging stations. In this way, already existing infrastructure in terms of power grid would be utilized as electricity would be distributed instead of hydrogen. This could prove to be a notable incentive for the local communities to engage in the transition, as distributed generation of hydrogen would provide many benefits to local communities directly, in terms of infrastructure benefits and jobs creation and indirectly, in terms of reduction of payments for importing fossil fuels. Active inclusion of citizens in the transition could give impetus to quicker adoption of the emerging technology.

3.3.2.3.3. Long-distance heavy-weight vehicles. One of the opportunities for the hydrogen is its use in long distance heavy-weight vehicles, such as trucks, unsuitable for current stage of development of battery electric vehicles. Nikola Motor Company unveiled its highly anticipated Nikola One fuel cell truck in December 2016 [98]. It has a range of 800-1200 miles while delivering over 1000 horsepower with zero emissions. In Norway, a recently started project is aiming for production of four hydrogen powered trucks and 10 forklifts for the largest food distribution company in Norway [99]. However, it is still unclear whether these trucks will use fuel cells or hydrogen internal combustion engines. Fuel cell stacks using Proton Exchange Membrane technology, suitable for use in trucks have already been produced and delivered in unnamed European company for testing [100].

Both barriers and opportunities are significant in terms of hydrogen driven transport sector. In future research it will be important to holistically model hydrogen conversion as a part of energy system, as production of hydrogen can increase flexibility of the power system, as well as significantly improve the air quality of the future cities. Too narrow focus on hydrogen technology itself does not capture these pros and thus, can lead to worse socio-economic indicators than it is in reality. Furthermore, the potential of local job creation in distributed hydrogen production infrastructure should be seriously investigated in the future, comparing the benefits of local production with the anticipated economies-of-scale of a mass, centralised production.

3.3.3. Biofuels

3.3.3.1. Economic barriers. One of the conclusions from the study that compares biofuel production and food security [101] was that “increasing biofuel production will have impact on world agricultural commodity prices and food security at global, national, household and individual levels”. Furthermore, authors in [102] estimated that increased biofuels production caused 12% rise in global food prices, of which US biofuel production accounts for 60% of the total rise.

Another argument is that biofuels have a potential to lower fossil fuel prices, creating therefore a “rebound effect” of returning to the fossil fuels [103].

Furthermore, a significant economic barrier can be seen in terms of available renewable biomass. Next to the transportation sector, both power and heat sectors are increasingly utilizing biomass as a form of the clean and renewable technology, lowering the amount of sustainable biomass available.

3.3.3.2. Technical (infrastructure & environmental) barriers. Authors in [3] summarized the main barriers of biofuels as follows: limited amount of residual bioenergy sources from agriculture, waste or forests; high land demand if the purpose of crops is only production of biofuels; land alternative for biofuel production is often food production. Life Cycle Assessment (LCA) of biomass-based energy systems performed in [104] showed that the use of crops to fulfil the biofuel demand for heavy transport, ships, defence and aviation caused significant environmental impacts on global warming, eutrophication and land usage.

One of the largest barriers of the biofuels is that the existing IC engines need to be optimized or re-designed in order to be suitable for biofuels, or biofuels need to be blended with the conventional fuels, which in turn leads to higher GHG emissions. Moreover, if the fuel is adapted to suit the existing technology, it is important to consider that the more the fuel is processed the lower is the overall system efficiency

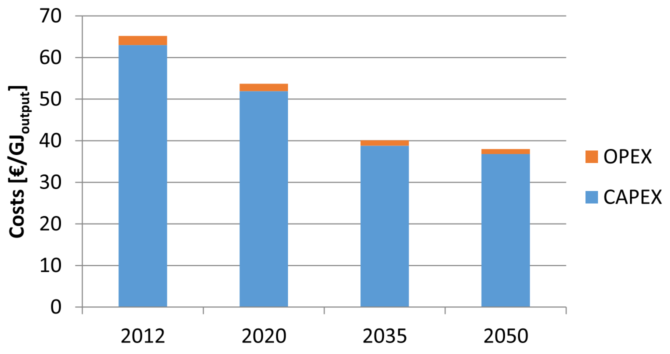

Fig. 3. CAPEX (Capital expenses) and OPEX (operating expenses) for DME production.

[105].

Furthermore, despite the fact that the cycle of producing and consuming biofuels is considered carbon neutral, if the biomass resources are utilized in a sustainable way, NO_x emissions of most biofuels are at a comparable level with the conventional diesel fuel [106]. Some studies found that biodiesel in some cases actually increases NO_x emissions, while it reduces hydrocarbons (HC), CO and PM emissions in comparison to the petroleum diesel fuel. The reasons for such an effect may lie in the influence of biofuels on injection time, ignition delay or combustion temperatures.

The study in [52] analysed the process chains to supply various fuels for the Singapore's aviation and marine sector, including biofuels produced from the crude palm oil, applying a well-to-tank analysis. It showed that looking at the overall life cycle of biofuels production from the palm oil, including cultivation of oil palms, extraction of oil, transport of oil and the final production of the fuel, results in the GHG emissions that can be even higher than emissions associated with the production of the conventional diesel fuel, depending on the palm cultivation rate. Moreover, a huge land use demand makes this type of fuel highly unlikely to replace a substantial level of traditional fuels in the future.

3.3.3.3. Opportunities. Advantages of using biofuels are however numerous, especially considering the current market and technology development state. Firstly, the cost of producing biofuels is considerably lower than the cost of producing hydrogen or synthetic and electrofuels, but currently still higher than the cost of producing fossil fuels. Next, they can be produced from a wide range of materials, from wood biomass and residuals to crops and edible oils. For example, on EU level several first, second and third generations of biofuel production technologies were considered [107]. It was found that the most promising raw materials for economical production of biofuels are miscanthus and algae, while biofuels could replace significantly more than 10% of the fossil fuels without significant impact on the EU's food supply chain. Finally, although biofuels have some negative impact on the air quality (increased NO_x emissions), they generally contribute in reducing GHG emissions, including CO_2, CO and especially PM [108].

Considering biomass, future research and technological advances should focus on the 2nd generation of biomass, in order to avoid the competition with food production land use. Moreover, a holistic modelling of the biomass supply chain is needed in order to assess its demand along with the biomass demand in heating and power sectors, as focusing only on the transport sector could lead to the excess use of biomass, making it unsustainable. On the other hand, even if the biomass use will be sustainable from the CO_2 point of view, rapidly increasing urban population will need to cope with high air pollution emissions from biofuels and thus, further technological advances in internal combustion engines (ICE) and the exhaust systems of vehicles will be needed in order to improve the socio-economic costs of the transport systems in the future. Due to its economically sound performance compared to the other alternative fuels, it should be considered as a potentially cost-competitive technology to fossil fuels, especially for the part of transport sector that is hard to electrify with the current state of technology, such as aviation and heavy duty vehicles.

3.3.4. Synthetic fuels utilizing intermittent renewable energy sources (PV)

Synthetic fuels can be produced by co-electrolysis from CO_2 and H_2O with the large amount of electricity. One of those fuels is DME and it is considered to be a viable substitute for diesel fuels, being able to use the same systems and infrastructure.

If the excess capacity for the synthetic fuel production exists in the energy system, it can significantly improve the integration of intermittent renewable energy sources as it can utilize the electricity generated in time when there is no other demand for it. The latter means that the technology can be used for effective demand-response management of electricity. Moreover, in the time with the lower electricity demand, it is natural to assume that the price of electricity will be low, following the supply and demand law. In order to assess the impact of electricity price on the total cost of synthetic fuel production, CAPEX (capital expenses) and OPEX (operating expenses), including the electricity costs, need to be assessed. Following the costs for DME production using the SOEC co-electrolysis (efficiency anticipated in 2020 65%) and syngas synthesis (efficiency today 71%) as calculated and reported in [66], a Fig. 3 was created.

On top of the costs presented in Fig. 3, the cost of electricity needs to be added. Price of electricity on a day-ahead market varies a lot. For the year 2015, in the DK-west node of Nordpool day ahead el-spot market the average spot price was 22.9 €/MWh, peak price 99.77 €/MWh and the trough price −31.41 €/MWh [109]. If one considers that the system would have excess capacity for production of synthetic fuels, it would be only used when the electricity is cheap. The lowest third of the el-spot prices for the year 2015 yields the average price of 11.31 €/MWh, peak price 19.19 €/MWh and the trough price −31.41 €/MWh. Recalculating the units and adding the average electricity price of 11.31 €/MWh yields the total price of generating a synthetic DME fuel of 64.84 €/GJ in 2015.

A significant barrier to this technology is a very small total efficiency. Efficiency of power-to-DME is 46% today and burning the fuel in the engine with approximate efficiency of 25% would lead to the total efficiency of only 11.5%. Even if arguing that synthetic fuels produced from renewable energy are CO_2 neutral, such a small efficiency is still a significant constraint for the future energy system.

If the current market structure remains in the future, the push of intermittent renewable energy sources will cause even larger number of hours with extremely high power production, which will not be followed by the high demand in the same period. It is out of the scope of this paper to discuss about the exact development of power prices in the future; the question that this paper will tackle is whether the falling prices of PVs can lead to the periods with extremely low electricity price which can then be used for the synthetic fuel production.

3.3.4.1. PV price drop. The PVs' price has tremendously dropped starting from 1970s. Crystalline silicon solar cell prices have fallen from 76.67 $/W in 1977 to 0.74 $/W in 2013 [110]. As there is no real constraint for mass production of PVs, it is expected that the price of PV systems will decrease even further. International Energy Agency (IEA) assumes the turnkey price in 2050 of 0.4 €/W [111] while study performed by Fraunhofer institute led to the price estimates between 0.28 and 0.61 €/W [112].

This low price of the PVs will probably cause a rapid penetration of it in the future, which will cause a significant increase of the critical excess in electricity production (CEEP), the amount of electricity that is produced but there is no demand for it in the real time.

One potential transition scenario to 100% renewable EU has been assessed as a part of the Smart Energy Europe study [63]. The study was carried out using EnergyPLAN modelling tool and it showed that the synthetic fuels are needed as the last step if the successful transition wants to be achieved. However, in this study only the modest amount of electricity generation from PVs was assumed, equal to 7.8% of the total electricity generation, while the assumed price of the technology used was 0.9 €/W. The whole study and the underlying model, as well as the modelling tool can be freely downloaded [68].

As the authors of this paper argued that the future PV price will be much lower than the 0.9 €/W, as discussed above, a significantly larger PV penetration level in the system can be expected. Hence, the authors of this paper used the case study, the model and the modelling tool as reported in [63] as a starting point for assessing the impact of lower PV price assumption on its economically feasible penetration level.

This study adopted the PV installation price of 0.4 €/W, as anticipated by the IEA, and used this number as input in the model developed as a part of Smart Energy Europe study (all other inputs remained the same as in the original study). PV penetration level was increasing with the 10% steps, starting from the level used in the Smart Energy Europe study and the total system costs were tracked for each change in PV capacity.

Fig. 4 shows that with the increase of the installed capacity of PVs, the total system cost drops significantly, while the CEEP increases by more than a factor of 2. There are two options of dealing with the excess electricity generation from renewable sources if there is no demand for it. The first one is to curtail the generation of electricity of intermittent renewable energy sources or to utilize this excess electricity generation by some flexible demand-response technology. In the latter case generation of synthetic fuels is a viable option, as the storage for the synthetic fuels is relatively cheap due to its ability to utilize already existing storage for liquid fuels. Furthermore, this electricity could be priced at near zero value, as otherwise it would be wasted (curtailed).

Electrofuels production utilizing intermittent renewable energy sources such as PV has a significant potential for integration of power and transport sectors. Potentially large amounts of cheap electricity in certain periods of time could drive down the running costs of electrofuels production. Furthermore, if the production of electrofuels will be decentralized, it could further enhance the local economic perspectives, on top of the local economic benefits provided by a more significant penetration of PV systems. However, there are still technology issues that need to be addressed, such as the lifetime of stacks during frequent ramping up and down of electrolysers and the efficiency of the SOEC itself. Moreover, air quality issues from utilizing electrofuels in ICEs could still be an issue in the densely populated cities, which needs to be thoroughly addressed in a systematic future research. Hence, in order to model all the mentioned points, electrofuels production needs to be modelled as a part of the whole energy system, in order to capture the interactions between intermittent sources rapidly decreasing in their price and demand for fuels in transport sector.

To sum up, Table 5 presents a qualitative assessment of the pros and cons of different technologies considered in this paper.

4. Discussion

Following the methods presented in the second section and results in the third section, several important issues can be discussed upon.

First, due to the high energy efficiency, possibility of integrating power and transport sectors, cleaner air and the reduction of CO_2 emissions, all the transport means that can be directly electrified should undergo this transition. There is no better alternative to this transition in energy terms and it is the first goal and the crucial target that should be achieved when modelling the sustainable future transportation system. On the other hand, a rapid electrification promoted by the authors raises up different security questions in terms of heavy dependency of the transport sector on the power grid. Different emergency scenarios for cases of natural disasters, such as floods or earthquakes, should be carried out in order to locate the critical points in security of technical systems and to assess the consequences on the society in general. Certainly, modelling of the security of supply will become more complex in the future as more interactions among different energy sectors will need to be taken into consideration.

Second, the transport sector should be assessed in the context together with the expected changes in the EU28 population growth, GDP growth, increase in the share of urban population and the expected rise in transport demand in different transport modes. In a business-as-usual scenario, majority of the future transport demand will occur intra-cities, its share in total energy consumption is expected to grow, as both passengers will travel more (connected with the leisure and business time) and more goods will be transported due to the expected GDP growth. Several facts need to be stated in order to support the latter statement: urban population of the EU28 is expected to grow from 75% to 85% by 2050 [113], the EU28 total population is expected to grow from today's 508 million inhabitants to 518.8 million in 2030 (2.1%) and 525.5 million in 2050 (3.4%) (around 0.1% per annum) [114]. Moreover, depending on the economic development pathway, the total GDP will be 19.5–30.5% higher in 2030 and 41.4–53.8% higher in 2050, according to the European Commission [115]. Expected annual growth of different transportation modes can be seen in Table 6, representing an overall growth of 44.7% in passenger-km and 89.6% in ton-km.

The projected yearly rise rate of 2.1% in the aviation transport mode is especially worrisome (keeping in mind its relatively large share in total transport energy demand of 14%), recalling the difficulties with the utilization of alternative fuels in this transport mode. Moreover, a bit newer research on the future air transport demand made by International Air Transport Association (IATA) forecasts 3.8% average annual increase in the number of air passenger journeys over the next 20 years, meaning that the number of journeys in 2034 will be 2.1 times higher than today [116]. However, that growth is predicted to be 2.4% in Europe, slightly more compared to the growth rate presented in Table 6. On the positive side, in terms of energy production, the growth in the air traffic will be compensated to some extent by the increased energy efficiency in that sector. The World Bank set the goal of achieving a global increase in the aviation fuel efficiency of 2% per annum by 2050 [117]. Finally, ever rising growth of tourism will need to be dealt with in the research on future transport transition, incorporating its specific demand in both travels to the destination and within the target destination. According to [118], there are 10 main drivers of growth in the transport demand and one of the main drivers is tourism. Travel and tourism industry today represent 9.8% of global GDP and it is forecasted to grow by 4% each year over the next

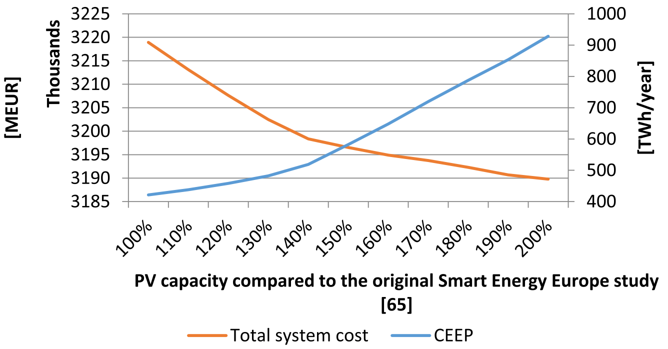

Fig. 4. Total system costs and CEEP values with the increase of installed capacity of PVs.

Table 5
Qualitative assessment of pros and cons of different alternatives.

	Economic barriers				**Infrastructure barriers**			
	High new infrastructure costs	High production costs	Low production efficiency	Influencing food price	Need new fuelling infrastructure	Need new supply chain	High land demand/ Sustainability problem	Intermittency friendly
Hydrogen	Yes[***]	Yes	Yes/No[**]	No	Yes	Yes	No	Yes[*]
Biofuels	No	No	No	Yes	No	No	Yes	No
Synthetic fuels	No	Yes	Yes	No	No	No	No	Yes[*]
PV for synthetic fuels	No	No	Yes	No	No	No	No	Yes

[*] If having excess production capacity in the system and produced using electricity from RES.
[**] Low efficiency of the complete cycle (well-to-wheel).
[***] In case of distributed production of hydrogen, existing power grid would be used removing the need for completely new hydrogen infrastructure.

Table 6
Annual growth in the transport demand in different transport modes in the period 2005–2050 [3].

	Road	Rail	Marine	Air	Total
Passenger	0.6%	2.7%	–	2.1%	0.8%
Freight	1.3%	2.3%	1.5%/2.0%[a]	–	1.4%

[a] within the EU/outside the EU.

10 years on a global scale [119]. This will have a significant impact on the transport demand, especially in the aviation sector.

Third, due to the still inadequate capacity and low energy density of batteries that are built into electric vehicles, the weight of vehicles when installing batteries with larger capacities significantly increases. Consequently, light vehicles frequently used for very long distances, a part of medium weight vehicles and majority of heavy weight vehicles cannot be directly electrified. Similarly, the aircraft mode is significantly impacted by the low energy density of current batteries and it is hard to foresee large commercial planes driven by electricity stored in the chemical form of energy in batteries. Hence, four different alternatives for these modes were evaluated and the results were presented in the former section.

Fourth, although a significant increase in the energy efficiency is achieved in the part of the transport that can be directly electrified, there is still a significant demand for fossil fuels that needs to be dealt with, i.e. 1125 TWh. Producing this amount of biofuels, as described in scenario 1, leads to the biomass demand of 3069 TWh (11,048 PJ). In the second scenario, the demand for biomass was 1279 TWh.

Sustainable potential of biomass was estimated in many different reports on the EU level. The European Commission estimated sustainable wood potential to be maximally 1698 TWh, provided that an intensive wood mobilisation efforts are applied [120]. The Biomass Energy Europe project compared more than 70 biomass potential assessments and they concluded that the biomass potential in different assessments varies considerably [121]. The mean reported constrained technical potential of the biomass at the EU level is around 3000 TWh. Finally, in [122], the estimated current biomass potential from agriculture was between 0.8 and 3.9 EJ (222 and 1083 TWh) and biomass potential from forests between 0.8 and 6 EJ (222 and 1667 TWh). Although the forest biomass potential is considered to be stable over time, the agriculture biomass potential could increase in the future. Taking mean values from the latter reference gives us the total potential of biomass for energy of 1600 TWh. Mean forecasted potential for the year 2050 from the same study is equal to 2360 TWh.

The European Commission reports that between 60–70% of the annual increment of the EU forests is harvested today, which means that there is only 30–40% of available biomass for further utilization. Having these numbers in mind, it is clear that there is no enough sustainable biomass resources for converting remaining part of the transportation sector to be driven by biofuels. Even the 1125 TWh of biomass demand for the second scenario would be extremely hard to meet in the sustainable way, as it would mean that all the non-harvested biomass potential of the future should be directed to the transportation sector. However, this is in collusion with the planners of power and heat sectors which also assume utilizing great amounts of the sustainable biomass potential in power and heat sectors.

This turns the discussion to the potential of synthetic fuels. Calculated increase in the demand for heat and electricity was 925 TWh and 2775 TWh, respectively. To have the sense of the amount of the additional energy needed, it is worth mentioning that the electricity demand in the entire EU in 2013 was 3100 TWh [123]. Hence, to meet the additional demand for generation of synthetic fuels, electricity generation in the EU should more than double. Here one needs to keep in mind that besides 2004 TWh of electricity demand for synthetic fuels, there is an additional demand for electricity of 880 TWh for the part of the transport sector that can be directly electrified. Even for the second scenario, in which the remaining part of the fossil fuels is replaced one part by biofuels and one part by synthetic fuels, the additional demand of 1646 TWh for electricity is challenging to meet. It is important to mention here that the heat energy demand for SOECs is a high-temperature one (between 700 °C and 800 °C). If high-temperature waste heat from some industrial processes would not be available, the share of energy demanded in a form of heat would also be generated from electricity, increasing the electricity demand even more.

A significant drop in PV price could have an indirect effect on the economy of synthetic fuels. Taking into a consideration the near zero electricity price in the time when there is a lack of demand for it, as shown in Fig. 4, as well as the drop of the technology costs for the production of synthetic fuels as calculated in [66], the expected cost of producing DME could be calculated to 38 €/GJ of fuel. A Gross price of one litre of diesel fuel is currently around 1.2 €/litre across the Europe. Using the lower heating value content of the diesel fuel of 39 MJ/l the calculated cost of the fuel for the end-consumer is 30.8 €/GJ, not including the negative health externalities. Hence, the production of synthetic fuels in the future could be cost competitive with the conventional fuels today, although historically it was proven to be extremely hard to forecast the tendency of the fossil fuel prices.

It is important to keep in mind that the direct cost for the end-consumer is not the only valid indicator for the energy system. Synthetic fuels allow the energy system to be more flexible as it can integrate different energy sectors, such as power, heating and gas sectors. Hence, there could be savings achieved in the energy system which cannot be directly valued as a part of the savings in fuel price.

Converting all the non-electrified parts of the transportation sector to hydrogen fuelled one can be extremely costly as well as questionable in terms of security. Infrastructure for hydrogen driven transportation sector should be built from scratch, as well as the whole supply chain on the global level. However, the latter consideration could be opposed by production of hydrogen in a distributed way using electrolysis. In this way, energy would be transferred using existing power grid, reducing the need for building a completely new infrastructure. Furthermore, it could foster local development, as opposed to the current large-scale remote drilling and refining stations used in the oil industry.

Furthermore, a lack of research focusing on the overall transport sector on a large geographical area and its interactions with other energy sectors has been detected. One of the more recent research papers dealt with the role of transport in the Smart Energy Systems framework [124]. According to the mentioned study, a solution for the transport sector are renewable electro-fuels produced from biomass and/or concentrated CO_2. However, two points need to be discussed upon. First, their calculated sustainable biomass consumption was 13.72 EJ/year (3810 TWh/year), which is possibly an overestimated value, based on the references presented in this study. The authors of this paper are of the opinion that due to the significant uncertainties in different studies on biomass potential, lower values of uncertainty region shall be used for energy planning. Second, the authors mentioned enormous capacity increase needed to reach their goals, i.e. 2750 GW of offshore wind, 900 GW onshore wind and 700 GW of PVs shall be installed by 2050 [124]. These totals in 4350 GW of needed capacity which is more than a fourfold increase compared to the currently installed capacity, being less than 1000 GW [125]. Hence, the authors of this paper would like to emphasize the latter point, which is in line with the very large energy requirements calculated for the alternatives in this paper, and argue that it will be highly complicated to reach the needed capacities. Furthermore, the needed capacities would be even larger, if one would adopt biomass potential argued in this paper.

Hence, the authors are of the position that the possibility of the transition of the transport sector's part that cannot be directly electrified could be found in emerging technologies, which would increase the efficiency of the transport sector, as opposed to the concept of synthetic fuels and/or renewable electrofuels which cause an increase in energy consumption overall. In total, seven promising emerging alternatives were detected in the literature review: delivery drones that could increase efficiencies along the commercial supply chains [126], public transportation combined with car hailing and car sharing possibilities [127], 3D printing that could allow distributed manufacturing processes, reducing the need for transporting manufactured parts [128], hydrogen in aviation such as zeppelins, some of which are being currently prototyped [129], catenary vehicles that could use electricity directly, without the need for large batteries [130], inductive charging, also reducing the need for large batteries [131] and Hyperloops, extremely high speed vehicles operating in specialized low-pressure tubes [132]. All the mentioned alternatives could significantly increase transport efficiency, avoiding the emissions in the first place. The authors would like to invite researchers to contribute more time towards assessing the potential of these technologies on the overall energy system.

Furthermore, as the urban population is expected to grow in the future, air pollution, especially in large cities, is a growing problem that has gained more attention recently [133]. Especially worrisome pollutant from the cars are NOx emissions, as well as PM2.5 in a lesser manner [135]. Considering this aspect, it is important to emphasize that combustion of synthetic fuels, renewable electrofuels and/or biofuels still produce NOx emissions and PM2.5, even if the CO_2 emissions would be argued as neutral, impacting the quality of life, especially in cities. According to the IEA, around 6.5 million deaths worldwide are attributed to the air pollution, much greater than the HIV/AIDS, tuberculosis and road injuries combined, being the 4th largest threat to the human health [133]. Hence, the authors argue that, already being very complex to carry out transition towards renewable transport sector, a future research should incorporate considerations about air quality in order to encompass both sustainable and renewable aspects of the future transport sector.

The literature review presented in the introduction section detected that most of the research focused on single sector solutions, or even focused on single technologies, such as electric cars. Some research for marine transport and/or aviation transport sectors was also carried out independently of the impact on the whole energy system, adding to the conclusion that there is currently a lack of systematic studies taking into account the transition in the transport sector and its impact on the other energy sectors. This study confirmed the importance of the holistic view when modelling transport sector and detected that, after the energy efficiency benefits achieved by directly electrifying one part of the energy sector, a significant energy resources would be needed for the final transition towards completely sustainable transport sector.

In order to address the latter and due to the ever increasing amount of emerging alternatives, with somewhat vague and ambiguous prospects, several different aspects should be taken into account in research in order to avoid ill-founded assumptions. First, the share of urban population will increase in the future, which will lead to more intra-cities transport demand, as well as raise the complexity of the transport patterns. Second, a constant rise in tourism activities will further burden the infrastructure and make the transport demand patterns less regular. Issues connected with the air pollution will be especially emphasized in ever-growing cities; hence, the harmful emission and particulate matter emitters should be reduced as much as possible. Third, enormous resources needed for the part of the transport that cannot be directly electrified by the current state of the technology development, should steer the researchers towards areas of research connected with the possibility to *reduce* or *avoid* transport demand. In order to promote the latter, a suitable approach could be to distinguish transformation in the transport sector between passenger transport and freight transport. The latter could be seriously tackled by technologies such as drone deliveries, modal shift from planes to ships or trains and 3D printing, fostering distributed production that avoids (or at least reduces) the need for transport. Passenger transport could benefit more from schemes such as increase in the public transportation presence, car hailing and car sharing schemes (as well as integration of the latter three technologies) and utilizing smart-data approach in future smart cities. The transition towards both sustainable and renewable transport sector will be neither easy nor harmless for some sectors and industries; however, prospects of cleaner, safer, sustainable and more affordable transport sector should overpower any obstacles on the way.

5. Conclusions

To sum up, several explicit conclusions can be made out of the proposed model and mapping of current transport situation and potential of renewable resources:

- ✓ All the transport means should be converted to electrified transportation modes if there is a technical possibility for it. Benefits of this transition are fourfold: reduced CO_2 emissions, increased energy efficiency, better air quality and the integration of different energy sectors.
- ✓ It is technically possible today to shift 72.3% of the fossil fuel demand in the transportation sector to the electricity. Following this transition, increased efficiency of the electrically driven transportation means will reduce the final energy demand in transportation sector for 50.6% or 2051 TWh.
- ✓ For the remaining part of the fossil fuels several alternatives exist. Due to the lower estimated well to wheel efficiency of the alternatives, a significant additional demand for resources occurs. In the case of replacement of remaining part of fossil fuels by biofuels,

additional biomass demand is equal to 3069 TWh. In the mixed scenario of biofuels and synthetic fuels additional demand for biomass, electricity and heat are 1279 TWh, 1646 TWh and 549 TWh, respectively. Finally, in the scenario with synthetic fuels used as a replacement for the remaining part of fossil fuels, additional demand for electricity and heat were 2775 TWh and 925 TWh. Additional demand for electricity in the latter scenario (including the demand of 880 TWh needed for electrified part of the transportation) is more than the total electricity demand of the whole EU in 2013.

✓ If the excess capacity for synthetic fuels production would exist in the system, excess electricity for which there is no demand could be utilized at the near-zero price. With the expected technology price drop until the year 2050, the price of producing DME, a potential substitute for diesel fuel, was estimated to be 38 €/GJ of fuel, which would be cost-competitive with the current end user fuel prices.

✓ Significant costs of building completely new infrastructure, as well as lower efficiency compared to the electric vehicles, could be too large burden for the wide scale development of the hydrogen driven transportation system, in spite of its benefits on the air pollution issue and the reduced CO_2 emissions. The Modal shift to railway transportation mode is also challenging in terms of infrastructure costs.

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