Transportation in a 100% renewable energy system

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A R T I C L E   I N F O

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A B S T R A C T

A 100% renewable economy would give a lasting solution to the challenges raised by climate change, energy security, sustainability, and pollution. The conversion of the present transport system appears to be one of the most difficult aspects of such renewable transition. This study reviews the technologies and systems that are being proposed or proven as alternative to fossil-fuel based transportation, and their prospects for their entry into the post-carbon era, from both technological and energetic viewpoints. The energetic cost of the transition from the current transportation system into global 100% renewable transportation is estimated, as well as the electrical energy required for the operation of the new renewable transportation sector. A 100% renewable transport providing the same service as global transport in 2014 would demand about 18% less energy. The main reduction is expected in road transport (69%), but the shipping and air sectors would notably increase their consumptions: 163% and 149%, respectively. The analysis concludes that a 100% renewable transportation is feasible, but not necessarily compatible with indefinite increase of resources consumption. The major material and energy limitations and obstacles of each transport sector for this transition are shown.

1. Introduction

Some of the major challenges that the present world economy faces are energy security, sustainability, pollution and climate change impacts. Some authors and organizations have defended a transition to a 100% renewable economy as a way to achieve an ultimate and lasting solution to these challenges [77,50,125,86,27,123,15]. That choice is based on the fact that renewables are already proven technologies, are experiencing rapid development and potentially have a zero carbon footprint. This last feature makes them especially appropriate to address climate change, which is probably the most urgent challenge that the global society faces [123].

In the medium term any renewable energy transition will probably be supported by intelligent use of fossil fuels, especially natural gas, which is a low-carbon dispatchable source that can complement intermittent renewables [84]. However, in the long term, our economy should become fully renewable according to some of the aforementioned studies. It would involve a major restructuring of infrastructure and an internationally coordinated policy action that would take between 40 [31] and 50 years [52]. Although such transition is urgently needed to avoid catastrophic climate change [123], governments have not yet supported such a coordinated policy initiative. García-Olivares and Ballabrer [52] assumed that a plausible date for the beginning of a global renewable transition might be the peak of all the fossil fuels production that is projected for between 2020 and 2036 by different authors [85], and its completion would take place in the second half of this century. That period of 50 years would also be compatible with the time that technological innovations have historically taken to expand throughout the economy [47].

In such a transition, the conversion of the present transport system appears to be one of the most difficult aspects. At present, global transport is still heavily dependent on fossil fuels (mostly, oil), that are expected to decline within a few decades [4,96,52]; furthermore, global transport produces a significant fraction of greenhouse gases, pollution in metropolitan areas, and is also a source of millions of accidents every year.

This study provides a review of global transport current conditions, behavior and uses, together with the main issues to be addressed to eventually achieve a fully decarbonized state for the global transport system. We try to answer the question of how a 100% renewable transport system could be built with proven technologies, what the transport system of a 100% renewable economy would look like, and what capital and energy costs the new system would have.

Transport is fundamental in the current globalized economy as it allows the exchange of goods, communication between citizens and is one of the causes of suburbanization in cities [49]. However, one of the major problems arising from the transformation of the global transport system is a high dependence on fossil fuels. In particular, oil is the main energy provider in the transport energy mix: over 94% of the total energy demand for transport is provided by oil, 3% by natural gas and
other fuels, 2% by biofuels and 1% by electricity, [66].

These general figures can be analyzed by considering transport modes or transportation use (by passengers or freight). Regarding passengers transportation, Light Duty Vehicles (LDVs) consumed around half of the total transport energy [67]. Freight transport consumed almost 45% of total transport energy in 2009, with Heavy Duty Vehicles (HDVs) using over half of that. If fuels were maintained as the main energy carriers of transportation in a 100% renewable economy, the synthesis of these fuels from electricity would consume a disproportionately large fraction of secondary energy [51]. In addition, this shows that a 100% renewable economy may face serious difficulties in growing beyond electricity production of 12 TWh/year. That power supply, and the biomass that would be sustainably available, would not be enough to simultaneously satisfy the energy demand, the demand for methane in ammonia production (for agriculture) and the synthetic production of hydrocarbons and olefins for the current size of the petrochemical industry. Thus, in such a scenario hydrocarbons would be scarce and expensive, and any direct use of the grid by the transport sector, if it were possible, would be the most economical option.

Thus, it seems wise to rationalize and restructure the transportation system towards making direct and intelligent use of electricity produced from renewables. The analysis below suggests that it is largely possible for land transport, but that air and marine transport may have to mainly use fuels produced from renewable energy.

Gilbert and Perl [55] identify a set of revolutionary changes to be implemented in the current transport system in pursuing transition strategies that can move more people and freight without oil before it becomes too late to avoid a global energy crisis. These authors probably undervalue the role that intelligent use of fossil fuels could have in a transport transition. However, they rightly point out the necessity to foster a transport revolution that refashions the present tight linkages between mobility and oil-based energy sources.

This is not the only reason to prefer a complete restructuring of transportation. As emphasized by Swenson [132], a direct replacement of the present fleet of internal combustion engines with an equally large vehicle fleet with electric motors would maintain the status quo in modern cities, which are overcrowded with cars and dangerous for pedestrians. In the MEDEAS project (“Modeling the Renewable Energy Transition in Europe”, European Union’s Horizon 2020 research and innovation program, grant agreement No 691287EU of the Framework Program for Research and Innovation actions, H2020-ICE-21-2015), the authors have studied different scenarios for Energy system development under environmental and socioeconomic constraints, with the objective to guide European policy toward a low-carbon economy. This study, which is part of that project, discusses some of the main technologies currently known or in prototype phase which could be used to substitute the current fossil fuel-based transport. We identify the transport modes that are more compatible with material and energy constraints. An estimation of the cost and energy required to implement such a transition has been also made.

The analysis describes the general structure of the world’s transportation system inside every important carrier subsector, that is, cars, ships, aviation, freight, urban transport, and so on. We expect future transport to be powered mainly by (1) electricity from onboard batteries, (2) the electric grid, and (3) hydrogen or methane to power fuel cells or internal combustion engines (ICE) of heavy duty vehicles, ships [65] and aircrafts, where the former means are not possible. We evaluate the current and perspective costs for these three sources in terms of energetic efficiency, availability of critical resources, and possible technological breakthroughs that may alleviate their flaws. The annual energy that a renewable transport system would use is also evaluated in Section 3.7 and, in particular, the energy cost of aircrafts if they were fueled with liquid hydrogen, liquid methane and jet fuel, respectively.

2. Materials and methods

For each transportation sector we discuss the main proven technologies, new infrastructure and policy measures that would make an optimal transition strategy. We identify the systems, infrastructure and policies that seem optimal according to feasibility and sustainability criteria. Finally, we compute the energy and monetary expenditures associated with the deployment of the new transport system. Variables such as efficiency of new transport systems and costs of the new transportation fleet are taken into account. When any variable is found to be too uncertain, e.g. the number of vehicles in a future electric fleet, we use conservative hypotheses such as assuming that this figure will be equal to the present one. For this reason, the scenario used for the final 100% renewable transportation in our cost calculations will not the optimal one that we can project.

2.1. Technologies and infrastructure for post-carbon transport

The main types of infrastructure, technologies and policy measurements which may be useful for urban, regional, marine, and air transport in a future 100% renewable economy are discussed in the following six subsections.

2.1.1. Electrification of urban and inter-urban transport

According to García-Olivares et al. [50] a future 100% RE economy would use an important fraction of present reserves of copper, lithium, nickel and platinum. The three latter metals will be used mainly in the transportation sector. The last metal would be used in fuel cells, which is a better option than batteries for motors requiring high autonomy and power, such as those of ships, heavy farming tractors, and a fraction of the fleet of trucks.

Hydrogen has been proposed as an energy carrier that is similar to oil and natural gas, and that could be used for land and marine transportation [43]. However, present electrolytic systems require around 60 kW·h to produce 1 kg of hydrogen [76], which implies an energy efficiency of 65% if we take Higher Heating Value (HHV) of hydrogen as output. This implies that hydrogen produced and consumed on-site has 1.53 times more electricity embedded than its own HHV content. If losses along the hydrogen conversion chain, i.e., containment, liquefaction, transport and handling are also taken into account, the result is that the production of hydrogen for consumption by a jet turbine or fuel cell requires 2.1 times its Lower Heating Value (LHV) energy content in the form of electricity [14].

In addition, electrical motors are more efficient than fuel cell motors (Table 2) and, for both reasons, a fuel cell vehicle requires 3.6 times more integrated electricity consumption than an electric vehicle [14]. Also, the hydrogen produced from wind electricity is estimated to cost 6.27 $/kg [99] if expressed in USD of 2015. If we use the low heating value of hydrogen (120.21 MJ/kg) and compare with the levelized cost of electricity production from wind turbines in the US (about 52 $/MW·h in USD of 2015, according to [39]) we find that hydrogen energy produced from wind is about four times more expensive than the direct use of wind electricity.

Thus, the direct use of electricity by motors is a cheaper and more efficient way to produce movement, and it may foster its spread in future ground transportation. The exception would be aircraft and other forms of transport that are not able to receive energy from the electric grid, as well as vehicles with specific requirements for both autonomy and power, such as ambulances, fire engines and police cars.

The most energetically efficient electric land transport for freight and passengers, are catenary-based systems such as trains and metro systems [134]. These seem appropriate for transport between cities and in metropolitan areas since the electric grid is dense in such areas. Widespread use of these systems would allow the reservation of electric vehicles (EV) for only short-distance transport between cities and populations not served by public transport [50]. It would allow saving of
energy and resources since 66% of the world population is expected to live in urban areas by 2050 [141] and metropolitan areas show a rising pattern, especially in western countries [120].

About 1117 million Light Duty Vehicles (LDV) (which includes 130 million light commercial vehicles), and 669 million two-three wheelers were in circulation in 2015 according to IEA [69]. The number of medium and high freight trucks was 32 and 24 million in 2015 [70]. The number of commercial vehicles that will use fuel cells is very dependent on the future weight given to trains for long distance freight. We will assume that this number will be only 10% of the number of light commercial vehicles and trucks, because with this percentage 59% of Pt reserves would have to be used in the fuel cell electrodes. The global demand for platinum has outgrown supply in recent decades and this is expected to worsen with the deployment of fuel-cell vehicles since hydrogen fuel-cells are the most advanced and utilized in this sector, and they require platinum as catalyst [153]. Direct use of other fuels, such as methane, is under research but it is uncertain if any will become economical. Currently, most methane fuel cell motors include a reformer that extracts hydrogen from the methane and then uses hydrogen fuel-cell [13].

Palladium mixed with a small amount of platinum (around 5%) is claimed to have a similar performance compared to pure platinum as a fuel cell catalyst, and in some aspects is even advantageous, for example, much less risk of CO poisoning [6,7,147]. Palladium is about 50 times more abundant than Pt, and at present is also cheaper. A number of other alternative non-platinum catalyst technologies are currently under study (see [124,79,103]), which raises solid hopes for working alternative to Pt within the next decade or so.

Lithium-ion batteries have the largest energy density and, for this reason, are the most widely used in electric cars today. Taking typical battery capacities and power for these three classes of vehicles (Table B.1) and the density of metal used in their respective motors (Table B.2), the quantity of lithium (Li) that such a fleet would require would be 9.1 Mt. Alternatively, nickel Na-NiCl2 (Zebra) batteries are technically feasible. If these batteries were used to renew the world fleet, 75 Mt of nickel would be used. These figures amount to 65% and 96% of present reserves of Li and Ni, respectively. If 50% of Li batteries and 50% of Ni batteries were used, 33% and 48% of the present reserves of Li and Ni would be used, respectively. Electric vehicles will be necessary, but given that reserves cannot be indefinitely expanded, the number of vehicles that a future post-carbon society could sustain is roughly the number we have currently. A larger number would probably endanger the availability of Li and Ni for other economic requirements.

These figures also imply the need to reserve the use of fuel cells for necessities that are absolutely essential and foster as far as possible the direct use of electricity by means of electric engines, as well as the convenience of reducing the current size of the car fleet as much as possible. García-Olivares [51] studied the demand of electricity, biomass, charcoal, biogas and metals in a 100% renewable industrial economy and concluded that a reduction of the present car fleet of about 50% would probably be desirable if we are to use the reserves of the above metals in future industrial necessities. However, in our calculations of Section 3, we assume that future land transport will instead be based on the electrification of the present vehicle fleet. The forecasts for future transportation consider an increase in the size of the future vehicles fleet [91,18,18]. However, such a trend may be balanced by a drift into policies fostering public transport or car sharing, and a reduction of the private car fleet. The size of the future fleet is uncertain because it is dependent on the policies that ultimately are implemented, therefore here we use that scenario to obtain an order of magnitude of the energy required.

A second reason to reduce the size of the car fleet is based on the problems that it causes on urban life. Some authors that advocate a model of healthy and efficient mobility in cities have warned that the electric car will not reduce the large number of accidents, abusive occupation of urban space, traffic congestion and sedentary lifestyle that the dominance of the private car entails [89].

A third reason is energy efficiency. Gasoline and diesel have an energy density of approximately 12-kWh per kg (10-kwh per liter), while lithium batteries used in electric vehicles (including modern Tesla batteries) are around 0.25-kwh per kg. That means that storing the energy contained in any fuel tank, let say, 50 L (with an approximate energy content of 500 kw-h) would require 141 kw-h of electricity (we have used the ratio of efficiencies given in Table 2 for internal combustion and battery motors), or a battery weighing 562 kg.

Even taking into account future improvements, most of the power of the vehicle will be wasted in carrying 1000 or 2000 kg of materials for the transport of one or two people and, in this regard, an electric vehicle (EV) makes no difference in relation to a gasoline one [89].

Four, a transport system for towns based on private EVs would require an electrified parking space (public or private) for every car owner, due to the necessity to recharge the electric car at night. In big cities this would involve the necessity for millions of electrified parking sites, which is a real challenge to implement. Future considerations about the implementation of the EV fleet will also include infrastructure changes to allow much greater electrical power supply at recharging sites than what is currently available.

If we want to solve the above problems, EVs will have a more limited role in future urban mobility than they do today. Public transport systems and light vehicles are alternative which could circumvent most of the mentioned handicaps. In parallel, shared electric cars could be encouraged in order to limit the numbers of private cars in large towns. Car sharing can be done in the form of a raise of the mean occupation (in terms of the number of passengers) and lowering of idle time, which for an average private car accounts for 90–95% of its daily usage. Prettenhofer and Steininger [110] estimated that 69% of household owning a car (681 million household if we use data from Table B.1) would economically benefit from a changing to a car sharing system.

This system could be combined with automation of EVs for mobility and freight distribution. The system has been tested in several urban environments across Europe in the frame of the European project CityMobil2 with promising results [5].

Other measures to develop a more energy efficient and sustainable transport system in future towns and cities would include (i) reducing transport demand, (ii) shifting transport ‘modes’ (from high to low energy intensity), (iii) improving energy efficiency through technological development [134], and (iv) boosting residential population in city centers to increase numbers of pedestrian walking to and from work, shopping, etc. [154].

The IPCC-AR5 [73] has also proposed a set of transport technologies and practices with potential for both short- and long-term de-carbonization and the transition to a 100% renewable transport system, in particular: (i) Modal shift with public transport, cycling and walking displacing private motor vehicle use; (ii) Urban planning by reducing distances within urban areas; (iii) Urban planning to reduce private motor vehicle use through parking and traffic restraint; (iv) Modal shift by reducing aircraft and Light Duty Vehicles (LDV) travel through high-speed rail alternatives; (v) Modal shift of freight by displacing High Duty Vehicles (HDV) towards railways.

2.1.2. Light electric vehicles and public transport for urban mobility

The present fleet of rickshaws, motorbikes and scooters could be replaced by a similar fleet of electric rickshaws, electric motorbikes, electric scooters and electric light quadricycles powered by rechargeable batteries. These light vehicles are more energetically efficient than low-occupation cars in kWh per passenger-km [134] and also require less nickel and lithium in their smaller batteries.

Electric skates, unicycles and hoverboards are also new technologies that may be useful for personal transportation in towns. E-bikes, electric mini-cars, quads, electric skates, unicycles, hoverboards, and pedelecs,
share a number of characteristics such as low weight and power (compared to a conventional car), low speed, and small size. This makes them essentially different from the model “electric car” as a substitute for the conventional gasoline car. Instead, they have the capability to exploit the potential of emerging technologies in the field of new materials (light and resistant), miniaturized electric motors, batteries, etc., without facing the insoluble problems that hinder attempts to replicate, with electricity, the performance of a conventional gasoline car. Thus, these new electric, light and personal urban transport vehicles could create a niche for themselves in a new type of mobility, mainly for urban areas, which adds to previously existent bike and car systems [89]. In this sense, the emergence of new types of electric vehicles should be accompanied by changes in normative and urban plans which help the most appropriate modes to generalize.

Bike sharing systems are also already implemented in many world cities (400 systems in operation in Europe in 2012 [33]) and are used as a regular means of transportation by people living in the city. However such sharing systems must be also supported by active policies from local (city), regional and national authorities to have an extensive impact on the habits of citizens with respect to the use of contemporary fossil-fuel based mobility vehicles.

Public transportation with systems connected to the grid include catenary-based systems such as light rail train, metro, commuter train and trolley bus [137]. These are the most energetically economic systems of transport, with consumptions of about 3.5, 4, 4.8 and 4.8 kWh per 100 passenger kilometers, respectively ([134], Fig. 12.14). Other economic systems according to the previous report are e-bikes (electric bikes) (1 kWh), e-scooters (2.5 kWh), e-rickshaw (4 kWh), and e-motorbikes (4.8 kWh). Electric cars have an acceptable efficiency with high occupation (4–6.5 kWh) but poor efficiency with low occupation (8.4–11 kWh). All these quoted figures have units of kWh per 100 passenger kilometers. Scooters, rickshaws and motorbikes have a similar efficiency but, contrary to catenary-based systems, require rare metals for the manufacturing of their batteries.

Bus rapid transit (BRT) is a known system that could be adapted for electric buses in future urban design schemes [45].

Cable cars and electric elevated cabins are other technologies that could be useful in a future 100% RE economy. One of the latter is the Solar-powered Automated Nonstop Elevated (SANE) transport system, a new system currently in prototype phase [132]. The system is similar to an urban network of trains/trams, but with the advantage that the support structure generates electricity for the elevated cabin motors with the help of photovoltaic panels that are able to produce as much as 1 MW per mile of line.

2.1.3. Metropolitan and regional transport

In megacities and metropolitan areas a modular shift from individual to more efficient public transport systems powered by renewable electricity is also possible in a decadal time frame and with currently available technologies. Gilbert and Perl [55] predict a possible continuation of the current level of freight movement between cities but with very much more of it by rail than by road and rising use of trains, metro and trolleybuses for municipal and inter-city passenger transport. Grid-connected vehicles (GCV) are more efficient than battery-electric vehicles (BEV) (as much as 95% compared to 80% of BEV) [48] and should be the first option in future transport planning.

Long distance terrestrial transport could benefit from a massive shift from trucks to electric trains (for freight) and from cars to public transport (for passengers). In particular, a train is able to transport about 8 times more people per MW than a car [53]. Trains and trolleybuses could be powered via overhead wire power-supply systems or via ground-level power-supply systems, like the APS system used for public transports in Bordeaux (France) [80]. Catenary systems are also currently being tested for truck transport on highways [35].

If a wide-power-supply grid is available for trucks, buses or cars (from catenary or ground), onboard battery-power will need to be used only to change lanes and for the “last mile” to destination. This makes it possible to minimize the size of batteries, since they can be re-charged during travelling on main roads, where external power-supplies are available.

Magnetic Levitation has also been proposed as a high-speed transportation system between cities. The main problem is the technological complexity and price. The Maglev from Pudong airport to Shanghai cost about $44 million per kilometer [139]. It is hard to believe that it may be a feasible scalable alternative for non-developed countries.

Aside from electric trains, other technologies are currently in prototype phases or starting to be commercialized:

1. Battery buses: Electric buses currently in prototype phase (such as the one designed by Proterra [111]) have a carrying capacity similar to gasoil buses and a similar range (600 km). Their deployment could take off at any moment if a minimal infrastructure for electrical recharging were built along highways.

2. Electric trucks: Trucks like the Mercedes urban eTruck with admissible weight of 26 t and lithium-ion batteries with autonomy for 200 km [36] are currently under development.

3. RUF system: Another proposal that could be used in a future 100% RE economy is the “Rapid Urban Flexible” (RUF) transport system [115]. It is based on a network of guideways between cities and metropolitan areas. The vehicles are driven manually for a few km on ordinary roads in order to get to the rail system. There the vehicles enter the guideway where they are coupled to form trains. The train of cars is powered by the electrical grid. A combination of windmills and solar cells can be integrated into the monorail system to ensure self-powered transportation. Between cities, drivers can relax until they get close to their destinations where they take over control again and drives manually to the final destination.

4. Another proposal is being developed in the so-called Tracked Electric Vehicle (TEV) Project [136]. It is based on an idea by the inventor Will Jones, who seeks to build special highways in which cars would not only be recharged while driving along them, but would also be driven autonomously (if the navigation system were incorporated into the vehicle). These highways would avoid traffic congestion by allowing cars to travel in a kind of vehicle train. Cars recharge during the ride using a Scalenelectric type electric system, or “twin rail”, installed in the center of the lane. Much of the electricity could come from solar panels placed on or above the road.

The two latter systems imply an international electric highway network with all countries using the same design standards. The TEV system is probably simpler since it does not require technical breakthroughs in car design; but the RUF system is relatively safer since it makes an accident by collision or loss of adhesion practically impossible.

These kinds of systems would rationalize private traffic in metropolitan areas and almost eliminate traffic accident casualties.

Many of these new types of infrastructure may require strong political intervention, especially when they oppose market and institutional inertia, easement rights, and so on. However, the magnitude of the challenges that we face to solve the problems outlined in the Introduction make this political intervention necessary to achieve the objectives in time [31,50,123].

2.1.4. Demand reduction

Three main strategies are suggested [73] for demand adaptation of future transport needs. Such strategies deal with the necessary demand reduction in a world with an increased total population. Three main aspects should be considered:

- Firstly, travel will need to be reduced. This may be achieved through technological improvements in information and communication technologies. Although there are barriers associated with different
broadband capacities in different regions, this will create market opportunities for improved video-conferencing system quality and remote working [57,23,149,156,153,118,94].

- Secondly, behavioral change. This involves reducing private motor vehicle use through pricing policies, e.g., highway charges and parking fees. While, initially, such changes may be unpopular with the public, they will provide opportunities for demonstrations of potential benefits such as better transport outcomes from combinations of pricing, traffic reduction, parking and investment in new infrastructure [87,85,118,26].

- Thirdly, behavioral change resulting from education on the benefits of less motor vehicle use. This may have immediate impacts of 10–15% reduction of Light Duty Vehicle use. In the long term this will produce significant emissions reductions only where quality transport alternatives are available. Despite the current lack of belief in the value of educational behavioral change by politicians and professionals, it is necessary to give demonstrations of ‘travel smart’ programs and explain the multiple benefits of such behavioral changes [106,56,133,9,64,118].

The emergence of a new model of “Transport as a Service” (TaaS) [8] may also contribute to a significant reduction in demand for private vehicles. This new model of urban mobility is expected to grow notably in the next decades, at least in western countries, due to lower affordability of private cars to the middle classes and the need to reduce the numbers of private vehicles in big cities.

2.1.5. Marine transport

Biofuels, natural gas and hydrogen have been proposed as fuels for ship propulsion [114]. Biofuels from food crops directly compete with agriculture for soils and, thus, may in the long term create more problems than they solve. Cellulosic ethanol is also problematic since it tends to draw nutrients from crop soils [12,82] and, in a post-carbon economy, will compete with olefins and methane production for crop wastes [51]. Biofuels from algae may become deployable in the next 10 years but first this approach must overcome a number of unsolved hurdles that make their becoming a globally available fuel uncertain [61].

Hydrogen use in ship propulsion is technologically feasible but is dependent on a major deployment of hydrogen infrastructure for production, storage, transportation and port services that, currently, is uncertain. Natural gas as a marine fuel could achieve climate parity within 30 years for diesel ignition engines [138], but it needs to be produced sustainably in a future 100% renewable economy.

Natural gas could be obtained sustainably from fermentation of farm and urban wastes and by combining electrolytic H₂ with CO₂ in the Sabatier process. In a post-carbon economy, the first process will also be the source of methane needed for the production of ammonia, at least during the necessary transition to fully organic agriculture. Therefore, the second process would be preferable in the long term. It may reach efficiencies of 55–56% if the heat produced in the reaction, and CO₂ exhausted by industrial processes, are reutilized (Gottz et al. 2016), [38]. Gas turbines represent a proven propulsion technology that could be used in marine transport [114]. Alternatively, high temperature solid oxide and molten carbonate fuel cells are currently being developed and show the most promise for ship propulsion. These two kinds of fuel cells may use methane and could be operative in a few decades [114]. A biogas economy would require less changes than a hydrogen economy in the marine and aviation sectors and would have lower security concerns.

New wind-based drives, such as new generation sails and Flettner rotors, may also be useful for replacement of a fraction of the engine fuels used in navigation [93,134]. Efficiency of Flettner rotors is currently poor and its future improvement is uncertain. However, a promising technology is SkySails [126], an automated towing kite system that is able to replace up to 7 MW of a ship’s main engine propulsion power. The system has superior performance to sails because it uses high altitude wind power.

In the short and medium terms, some studies propose hybrid approaches to optimize the energy systems on ships. For instance, for a typical oil tanker, the optimal system on a ship consists of a 300 kW photovoltaic system, 2000 kW of diesel generators, 10 batteries and 200 kW of power converters, which is capable of reducing fuel-consumption by 2,010,475 L over 25 years [32].

2.1.6. Air transport

A decline in intercontinental travel is probable in a post-carbon economy. Its fall could be rapid because of economic decline or because no reasonable substitute for oil-fueled aviation emerges [55]. This prediction agrees with the conclusions of García-Olivares [51]: the energy cost of a future aviation sector of comparable size to that of 2005 would be 2.1 times higher than the current cost, which will probably further increase the cost of air travel. This may be compared with the relatively low utility contributed by this mode of transport: 0.7% of world freight (to be compared with 81.5% for shipping, 9% for rail, and 8.8% by road) and 10.6% of world passenger transport (to be compared with 82.7% by road, 6.3% by train and 0.3% by ship) [112]. In this context a future shrinkage in the numbers of passenger-km transported by air is probable.

Looking at technology trends for the next decade, the possibility for solar powered aircraft systems exists, which would add to the small airplanes in the current system that are appropriate for small freight and low numbers of passengers [1]. However, contemporary jet planes have no electric substitute with current known technologies. The only suitable renewable alternative would be jets powered by jet biofuels, liquid hydrogen or liquid methane [29], which would be obtained from electricity and biogilders. Jet biofuels could be directly used in existing aircraft engines with only minor modifications, thus avoiding the building of new airport infrastructure for fuel storage. However, if biofuel is produced from methane via the Fischer-Tropsch process, the energy efficiency of the process is about 0.59 [37]. Combining this efficiency with the efficiency of the electricity-to-gas process (0.4, see Table 2) the result is an efficiency of 0.24 for the electricity-to-jet fuel process. To waste 60% of renewable energy supply, instead of 76%, to produce aircraft fuel can make a difference in an economy with difficulties to increase its primary energy production. For this reason, the scenario that we assume in our calculation is that, in the long term, airport infrastructure will be built to store and use methane as a fuel for future aircraft.

2.2. Calculations

This section briefly discusses some potential sources of the investments that are required for a 100% renewable transport system as well as the calculation method employed to estimate the costs of fixed capital and embedded energy for new transport fleets and infrastructure.

2.2.1. Investment required for a 100% renewable transport system

We make estimates of the order of magnitude of the investment required for the transformation of the present transport system into a 100% renewable energy-based transport system. In particular, we estimate the gross investment in fixed capital of the transition. Then, the energy embedded in that capital is estimated.

To support sustainable transport system development, eight multilateral development banks have pledged to invest around 170 billion $USD (dollars of 2010) between 2013 and 2023 [90,73]. A major part of the funding for sustainable transport could arise from redirection of existing funds away from unsustainable transport [117,143,273]. For instance, a major part of the cost that we calculate should be shifted into a 100% renewable fleet of vehicles may be found in the investment that is saved in the renewal of the old fleet. In addition, land-based taxes or fees can be offset by the value gains brought by sustainable
transport infrastructure [21,60,116].

In many cases the hypotheses that we assume here are a minimum energy calculation, because we are not considering additional costs associated with the creation of a complete support and maintenance infrastructure for a new electric transport system. In the future these calculations can be revised and completed with some factors that currently, as a first exploration, we are not considering.

2.2.2. Calculation method

We will assume that the current fleet of vehicles, trains, ships, and 50% of the present fleet of aircraft will need to be fully replaced with an equal number of transport units which will use electricity or biogas.

We calculate the cost in USD of such replacements for each transport sector, by using the current market price of the main classes of transport units. Then, we estimate the corresponding production cost by assuming that commercial margins for the vehicle, shipbuilding, aircraft and train building industry are 7% [130], 3% [11], 14% [155] and 20% ([34], Table 4.4), respectively. For civil construction (railways, highways) we assume a commercial range of 10% [63]. The marginal rate for aircraft building is estimated by averaging the mean margin reported for Boeing and Airbus over the last 5 years (2013–2017).

To translate the production cost to the net energy required to feed this investment, we use the energy intensity of national and global industries in 2016. As an example, the energy intensity of global industry in 2016 was 0.11 koe/USD2005, according to the World Energy Council [152]. Here Koe means kg of oil equivalent and $USD2005 means dollars at constant exchange rate, price and purchasing power parities for the year 2005. However, transportation equipment manufacturing is one of the most energy efficient sectors of the industry. Its mean energy intensity was 12% of the mean energy intensity of global industry in the year 2000 [92], and this ratio is apparently not very different in more recent industrial economies: 13.8% in California, 2008 [30]. Therefore, we systematically multiply the industry energy intensities by a factor of 0.12 to estimate the corresponding energy intensity of the transportation equipment sector for individual countries and the world.

We take into account the inflation of the dollar between 2005 and 2016, which was 24.7%. Therefore:

\[
0.11 \text{koe/\$USD2005} = 0.11 \text{koe}/(1.247\$\text{USD2016})
\]

Hereinafter, $USD2016 and USD will mean dollars at constant exchange rate, price and purchasing power parities for the year 2016. In cases where the manufacture of a type of transport unit is monopolized by a few countries, the industry energy intensity of these countries will be used in the calculation.

Energy intensities in industry and, in particular, in transport equipment manufacturing are expected to decrease as an increasing number of processes become fully electrified. García-Olivares ([51], see Table 5) showed that the transport equipment industry in a 100% renewable economy would use 87% of secondary energy to produce the same output as the corresponding sector of a fossil fuel-based economy.

To estimate the possible evolution of this energy density during the transition period between the present industry and a future 100% renewable industry, we will assume that the electrical energy used by the sector evolves from 2014 according to the contribution of new renewables, until 87% of the energy $p_{14}$ used in 2014 is reached. Over the same period, the fossil fuel contribution to the total energy consumed by the sector ($p_{14}$) is made to decrease until it reaches zero.

The fossil fuel contribution must decrease slowly at the beginning and then at an increasingly higher rate that is sufficient to maintain a monotonic decrease of $p_{14}$ between $p_{14}$ and final energy production $p_{f} = 0.87 \times p_{14}$. Appendix A shows a heuristic transition scenario to project the evolution of the energy density between the present economy and a future 100% renewable one. The energy density decreases 87% during that transition, with a mean value of 93% of the present value. Thus, in our calculations of energy densities we multiply the present values of these parameters by a factor 0.93.

To express the result in Joules we use the conversion: 1 koe = 41,868,000 J.

3. Results

In this section we analyze the investment and energy cost of transport by mode. In the case of trains, the cost of railways electrification is also included. We also estimate the infrastructure costs of storage and transport of liquid methane for marine and air transport, the building of charging station infrastructure to supply electricity to fleets of battery-powered vehicles, and the building of a TEV system of dynamical power and recharge (Section 2.1.3) across all the world’s roads. Finally, the annual energy used by the new renewable transport system is estimated and compared with the demand for transportation in 2014.

3.1. Light duty vehicles, medium freight trucks and heavy freight trucks

The cost of a transition to a post-carbon land vehicle system will be dependent on the mobility and shipment models that succeed, especially in urban and inter-urban traffic. However, here we will be conservative and assume that the entire present vehicle fleet will be fully replaced by battery powered and fuel-cell vehicles.

Concerning motorcycles, today there are around 669 million two or three wheel motorcycles in circulation globally. Around 50 million of these (mostly internal combustion engines) are sold worldwide every year. In 2015, expected sales of electric mid-size and large two-wheelers were about 4.3 million [150]. Hence, 10 times more would have to be sold annually within a few decades to ensure a successful transition.

Following IRENA [74,75], energy consumption of motorbikes is 0.1 MJ/passenger-km and the infrastructure, and associated costs are: 50–150 EUR/passenger-km. This is pointed to as an option to lower the energy requirements for some short distance transport uses for the conventional modes of city transport, and also as a feeder for public transportation. This transport mode, however, requires dedicated infrastructure that is coordinated and planned together with options for walking [70].

Another way to save on capital investment is to increase fleets of city and inter-city buses in substitution for cars. Current global energy consumption of city buses is 0.32–0.91 MJ/passenger-km, and the associated infrastructure costs: 200–500 EUR/passenger-km. For long distance buses energy consumption is 0.24 MJ/passenger-km and infrastructure costs are 500–600 EUR/passenger-km [74,75]. Buses have an average of 9000 (urban) to 17,000 (road) passengers per hour.

Sticking to conservative estimates, we will not consider these possibilities for savings and calculate the costs of renewal of the present fleet of motorcycles, light vehicles and heavy vehicles as is. This would involve the production of 1117 million Light Duty Vehicles [69] running on battery-powered motors (or fuel cell-based motors), 669 million electric motorcycles, 32 million medium freight trucks and 24 million high freight trucks [70] with fuel cells or batteries (Section 2.1.1 and Table 8.1 of Appendix B).

Maximum authorized mass defines the limit between light and heavy vehicles. This limit ranges from 3.5 to 7 tons in different countries ([102], see “Definitions”). In the same table we display the typical price of a median model of each class. We assume that 10% of light and heavy commercial vehicles will have fuel cell motors (those dedicated to high-powered and high autonomy tasks).

We assume that the retail price of a battery or fuel cell vehicle is twice the price of a conventional one. This is within the range projected by Plotkin et al. [108] for 2015 (see their Figs. 3–5a). Thus, the typical market price of EVs is taken as follows: USD 22,000 for light vehicles,
5500 USD for motorcycles and 100,000 USD for medium freight trucks (twice the price of the 180-kw JAC 4 × 2 lorry Truck, and the estimated price of the Tesla Semi electric Truck [131]. The price of an electric high freight truck is taken as twice that of the 455-HP Volvo D13 EcoTor tractor unit [54] (Table B.1).

The main reason for the additional cost of Electric Vehicles (EV) is the price of the batteries (besides the fact that the EV industry and EV consumer market are relatively young, as are the engines, chassis, etc.). Moreover, the engines tend to be simpler, lighter and somewhat cheaper, even with present technology.

Current fully-electric cars range in capacity from 20 to 50 kWh (for the Tesla S it is 60–100, see Tesla [135]). According to Nykvist and Nilsson [100] the cost estimate for 1 kWh in 2030 ranges from $200 to $300 (US 2014 dollars). Taking the midpoints of these ranges: capacity = 40 kWh, cost per kWh = $250, this results in $10,000 additional cost coming from the battery. According to some estimates, EVs will become cheaper than conventional cars by the mid-2020s [20]. However, in our estimation we have used the current typical prices.

The expression used to estimate the total capital cost in USD for the new fleet ($c_{v}$) is the following:

$$c_v = (1-m)(n_1p_1 + n_2p_2 + n_{md}p_{md} + n_{h}p_{h})$$

where $m$ is the commercial margin of the sector (assumed to be 7/100), $n_1$, $n_2$, $n_{md}$ and $n_{h}$ are the number of light vehicles, two-three wheelers, medium duty trucks and high duty trucks, and $p_1$, $p_2$, $p_{md}$ and $p_{h}$ are the typical market prices of these kinds of vehicles in their electric version, in 2017.

The final result is 3.6 × 10^{13} USD.

To calculate the energy embedded ($e_{v}$) in this capital, we have used the energy intensities [152] of the industry of the 39 main producer countries of cars and commercial vehicles. These countries are reported by the International Organization of Motor Vehicle Manufacturers [102]. The expression used is the following:

$$e_v = \frac{c_v}{10^3N} \sum_{j=1}^{40} e_j(0.12j)$$

where $c_v$ is the capital cost in dollars of the new vehicle fleet, $b$ is a factor of conversion from koe to Joules, 1.247 is an inflation factor for 2005 through 2016, $N$ is the global production of vehicles in 2015, $n_j$ is the number of vehicles produced by each country $j$ that year, $e_j$ is the energy intensity of the industry of country $j$ and 0.12 is the ratio to estimate the energy intensity of the transport equipment sector. The category $j = 40$ corresponds to «other countries» for which we use the mean global industry energy intensity.

The energy intensity in 2016 of different countries is estimated by extrapolating two years of the respective trend displayed by the World Energy Council [152] until 2014. The result (koe per $USD 2016) is displayed in Table B3 of Appendix B.

With these parameters, the energy required for the conversion of the global vehicle fleet would be $1.5 \times 10^{17}$ J (which is around one year of world oil production).

### 3.2. Shipping: marine transport

Let us consider now the capital cost required to building a global fleet of ships with new motors, that are different from the present day diesel engines.

We start by calculating the transformation of the global merchant fleet, and we also consider fishing boats even though they do not belong to the transport sector. The numbers and subclasses of merchant ships have been taken from Statista [127]. We will assume in the following that the building cost of a new battery or fuel-cell ship is close to the market price of a similar ship with an ICE (Internal Combustion Engine) motor. Today a number of existing ship designs feature electric propulsion (e.g., the superliner “Queen Mary 2”). These have a number of important advantages, in particular, they avoid the need for sophisticated and heavy shaft systems. This suggests that the difference in construction and operation costs would stem principally from the interplay of engines and fuel cell costs (or batteries), with the rest coming in favor of electric ships. Other future ships will probably use ICE powered by methane and other fuels, and in this case the new engines will have little difference from the old ones. An alternative to the use of methane in marine and air transport would be the use of biofuels, or heavy hydrocarbons obtained synthetically from methane and hydrogen. However these alternatives are energetically expensive and would put additional pressure on the electricity and renewable energy supplies of a 100% renewable economy (see Introduction). For this reason, we assume that methane will be the main marine and air fuel in the future economy.

The expression used to estimate the capital fixed cost of the entire shipping fleet ($c_{sh}$) is the following:

$$c_{sh} = (1-m)(p_{br} + p_{sh} + p_{au} + p_{hs})$$

where $m$ is the commercial margin of the sector (assumed to be 3/100) and $p_{br}$, $p_{sh}$, $p_{au}$ and $p_{hs}$ represent the aggregate price of the fleet of passenger, chemical, container, cargo, and bulk carrier, respectively. Cost of fishing vessels are calculated separately. To obtain these aggregate prices we consider the number and typical prices of different sub-categories of ship in each of the cited categories, as explained in Appendix C.

The total cost of the global transport fleet would amount to: $1.1 \times 10^{19}$ USD.

To estimate the energy embedded in this capital ($e_{sh}$), the mean energy intensity of the main ship exporters is used [142]. The share in world export of the main floating structure exporters is summarized in Table C.3 of Appendix C.

The expression used is the following:

$$e_{sh} = \frac{c_{sh}}{10^3w_s} \sum_{j=1}^{15} e_j(0.12j)$$

where $b$ is the koe to Joules conversion factor, 1.247 is the inflation factor between 2005 and 2016, $w_s$ is the world export of floating structures between 2013 and 2016; $e_1$ to $e_{15}$ are the exports of floating structures of the following countries or group of countries, between 2013 and 2016: South Korea, China, Japan, Germany, Poland, Brazil, India, Italy, Netherland, USA, France, Saudi Arabia, UK, Singapore and others (Table C.3 of Appendix C); and $e_1$ to $e_{15}$ are the energy intensities of the industry for these countries or groups of countries (Table B.3 of Appendix B). The energy intensity for Singapore is not reported and is taken as equal to the world average.

The result is: $4.8 \times 10^{17}$ J. These calculations have not considered the possible capital savings that may arise if navigation speed is reduced [25] or complementary traction (kites, photovoltaic panels) is included [93], which would allow reductions of the power of the main motors.

### 3.3. Air transport

In the next two decades rising demand suggests the aircraft fleet could increase from about 26,100 planes today to 63,220 aircrafts by 2037 [95]. However, in the longer term, a certain decrease in the demand of flights is probable in a post-carbon economy due to increased prices. In Section 4 we discuss how the number of aircraft in a 100% renewable transport system may lie between 35% and 50% of the present aircraft fleet. We estimate the costs of aircraft infrastructure under the assumption for these two reduced fleet scenarios, and also, for reference, assuming that all the 2017 fleet of aircrafts will be maintained in a 100% renewable transport system. From the projected 63,220 aircraft, 3918 would be regional, less than 100 seats; 45,055 “narrowbodies” 100–210 seat; 10,685 intermediate “widebodies”; and
3562 large widebodies. We have used the fractions of new passenger jets projected by Forsberg [46] for deliveries between 2014 and 2033. To these fractions we add the future numbers of freighters, projected to be 600 small freighters, 1300 medium size freighters, and 1000 large freighters by 2032 [3]. With these figures, we estimate the fractions of different kinds of planes that might be used in the near future (Table D.1 of Appendix D) and assume that the same share of different aircraft types will be maintained during the ongoing reduction of the overall fleet. Current prices for the different aircraft types have been estimated as the average of the aircraft prices shown in the second column of Table D.1 (data from an Internet search).

We assume that the manufacturing cost of a new aircraft of any particular type that is powered with methane is the same as the cost of an equivalent conventional kerosene powered aircraft. Then, the cost of a full substitution of the aircraft fleet of 2032 \((c_{oa})\) is estimated with the following expression:

\[ c_{oa} = (1 - m) \sum_{j=1}^{7} n_j p_j \]

where \(m\) is the commercial margin of the sector (assumed to be 14/100), \(n_j\) is the number of aircrafts of type \(j\) and \(p_j\) its mean price, shown in the third and fifth columns of Table D.1 (Appendix D).

The final result amounts to 7.68 × 10^{12} USD.

Energy intensity for the manufacture of small freighter aircraft is assumed to be equivalent to that of the world transport equipment industry in 2016; for medium and large freighters, we use the mean energy intensity of the country where Boeing has its factories (USA) and the mean energy intensity of the four countries where Airbus has its main factories (Germany, France, UK and Spain); for regional aircrafts, we use the average between the energy intensity of Embraer (calculated from the energy intensities of the countries where Embraer has its factories: Brasil, China, USA and Portugal) and the energy intensity of Mitsubishi, assumed to be equal to that of Japan. Energy intensities of the entire industry can be found in Table B.3 of Appendix B; these can be converted to transport equipment industry energy intensities using a factor of 0.12. For narrowbody, Intermediate widebody and Large widebody classes, we use the average between the energy intensities of Airbus and Boeing, estimated as described above. The expression used to estimate the embodied energy in the fixed capital of the new aircraft fleet \((c_{oc})\) is the following:

\[ c_{oc} = (1 - m) \sum_{j=1}^{7} n_j p_j (0.12 i_j) \]

where \(i_j\) is the energy intensity of the seven kinds of aircraft and the other parameters have been defined above. The final result is \(4 \times 10^{17}\) J.

### 3.4. Railways

As an average global estimate, city tram energy consumption is about 0.53–0.65 MJ/passenger-km, and the associated infrastructure costs are 2500–7000 EUR/passenger-km. For long distance train, energy consumption is 0.15–0.35 MJ/passenger-km, and the current infrastructure costs are 15,000–60,000 EUR/passenger-km [74,75]. Taking these estimates into account, we make an approximate calculation of the cost of transition for this mode of transportation. Locomotives cost about 70,000 euros per unit, they cover 120,000 km/a and 106 km at the cost of transition for this mode of transportation. Locomotives cost 1.5 million euros per km per year to operate and maintain, this includes fuel, labor, and maintenance costs. The associated infrastructure cost is estimated to be 0.37 × 10^6 euros per km. The total length of world’s railways was about 1,342,010 km in 2013 [97]. We can assume that 50% of it is one-way rail (single catenary), 25% two-way rail (double catenary) and 25% two-way high speed rail. The cost of electrification of the world railway system \((c_{er})\) is estimated with the following expression:

\[ c_{er} = l (c_1 0.5 + c_2 0.25 + c_3 0.25) (1 - m) \]

where \(l\) is the world railway track length; \(m\) is the commercial margin of the sector, assumed to be the typical value for the construction sector: 10/100 [63]; and \(c_1\), \(c_2\) and \(c_3\) are the typical costs of single rail, double rail and high speed double rail electrification, respectively. The final result is \(4.6 \times 10^{11}\) USD, and the embodied energy would be \(1.9 \times 10^{17}\) J, relatively small figures compared to the previous costs for vehicles and ships.

### 3.5. Electrical charging system

An essentially electrical fleet of vehicles would need some form of power or recharge system. We consider two scenarios for this: (i) a global system of electric charging posts placed in urban streets, and (ii) the global deployment of the TEV system of dynamical power and recharge (Section 2.1.3). The average world distance traveled by car in towns and metropolitan areas \((c_{oa})\) was about 3800 km per person during the year 2012 [140]. Electric cars in today’s market use chargers that are able to supply sufficient charge for 55–125 km of autonomy in one hour [119]. Let us take \(a_0 = 80\) km autonomy per hour of charge as a median value. If we take \(o = 1.5\) passengers per car as a typical “low occupation” value, we find that, with this mean occupation, 31.7 h of charge are required per person per year to meet the global demand for car mobility.

Assuming that a fraction \(f\) of the available electric recharging posts are unoccupied, the number of posts required for a city of \(N\) inhabitants can be calculated with the following expression:

\[ N_p = N c_{oa} [1 + f] / (8760 a_0 o) \]

where 8760 is the number of hours in one year, and the other variables have been defined above. As an example, the city of Barcelona \((N = 1.6 \times 10^6\) inhabitants and 102 km² of surface) with the world mean car mobility would need 68 recharging posts per km². Car mobility is much higher in the USA, about 13,000 miles per year [16]. With the US mean mobility, a city of the size of New York would require 204 posts per km². The block of building in the Eixample district of Barcelona, with the associated lanes included, measures 133.3 m × 133.3 m. Thus, we would have 1.2 and 3.6 posts per block with world and US mobility, respectively.

The cheapest recharging post of 22 kW offered by wallbox.eu costs 1207 euros per connection [146]. With this post, a typical car battery of 24 kWh may be recharged in just over an hour. We assume that this cost is close to the cost of production. The total cost of installing charging posts for global mobility demand \((c_{op})\) is estimated with the
following expression:
\[ c_{pi} = 1207 \times 1.2w_i \times h_i \times d / (24 \times 365) \]

where \( w_i \) is the world’s population in 2017, \( d \) is the euro-to-USD factor, \( h_i \) is the number of hours of charging that corresponds to the average person driving a low occupancy car (1.5 persons per car), which is calculated as \( h_i = 3800 / (\alpha \times 1.5) \), where \( \alpha \) is the autonomy per hour of charging (assumed to be 80 h).

At the time of writing the world population was 7515 million people. Using the mean mobility demand and a conversion 1 euro = 1.2 USD, we obtain \( c_{p1} = 4.7 \times 10^{10} \) USD.

This figure may give the order of magnitude of the costs associated with the charging posts necessary for mobility. Now we estimate the corresponding cost associated with charging posts to power commercial vehicles. The number and energy consumption of the global fleet of commercial vehicles has been obtained from IEA [69,70] and is summarized in Table 1.

The annual energy consumed per vehicle of each class (\( e_{d1} \) to \( e_{d4} \)) is obtained by dividing the corresponding values in figure 2 and 3 of Table 1. The power (\( p_{d1} \) to \( p_{d4} \)) of the charging post used by three-wheelers, light, medium and heavy vehicles are assumed to be 22, 22, 55 and 100 kW, respectively. With the battery capacities from Table B.1, the typical recharging time of the four kind of vehicles would be about 3 min, 1 h, 2 h, and 7 h, respectively.

The annual accumulated charging time of the vehicle of kind-\( i \) (\( t_{ui} \)) may be calculated with the following expression:
\[ t_{ui} = \frac{e_{d1} c_f}{p_{d1}} \]

where \( i \) is an index running from 1 to 4, for the four vehicles of each class, \( c_f \) is the conversion factor from joules to kwh, and the other symbols have been defined in the previous paragraph.

The cost \( c_{p2} \) of the recharging stations for commercial vehicles is then estimated from the following expression:
\[ c_{p2} = \frac{p_{d1} \times t_{ui}}{8760 f} \]

where \( f \) is the occupation fraction of the charging posts, here assumed to be 0.5, 8760 is the number of hours in one year, \( p \) is the mean price of a single charging station, and \( t_{ui} \) is calculated using the previous equation. The price \( p \) is uncertain given that high-power charging stations are not yet common in the market, but here we assume that it is equal to that of the Modo-4 Raption Trio model of Wallbox [146], 37,200 USD. The result is \( c_{p2} = 3.2 \times 10^{10} \) USD, and the cost of the totality of posts: \( c_p = c_{p1} + c_{d1} = 7.9 \times 10^{10} \) USD.

Using the world mean energy intensity of the sector, the energy embodied in that fixed capital would be \( e_p = 3.3 \times 10^{16} \) J.

Now we consider the scenario (ii) and estimate the cost of building a lane with the TEV system in all the world’s roads. A global system like this would allow us to reduce the number of fuel-cell vehicles to only those that need travel off-road and also allow us to decrease the size of the vehicles’ batteries. The total length of the world’s roadways was estimated in 2013 to be 65,285,000 km [24].

The building cost of one mile of this system in 1996 was approximately 2.5 million USD ([136], chap. 12) if the work were done from scratch. However, we assume that the work is carried out on already built roads. Thus, the cost should be similar to that for the electrification of a high speed double track railway line, i.e., 0.75 \times 10^6 euros (900 thousand USD) per km (Section 3.4). Thus, assuming a commercial margin of 10% for large civil infrastructure, the total fixed capital cost of deploying a global TEV system (\( c_{st} \)) can be estimated with the following expression:
\[ c_{st} = 900,000 \times l \times 0.90 \]

where \( l \) is the length of the world roads.

The result is \( c_{st} = 5.3 \times 10^{13} \) USD. Using the world energy intensity of transport equipment, the corresponding embodied energy would be \( 2.2 \times 10^{19} \) J.

3.6. Infrastructure for gas storage and transport

Infrastructure for transport and storage of methane will be required to fuel the demand of ports and airports. We will obtain here an order of magnitude estimate of the cost of the basic infrastructure needed to address such demand. We assume 300 km as a typical distance between refineries producing methane—from electricity and CO₂—and the points of consumption. This distance is typical in the current European Union for locations that are far from their nearest refineries.

We assume that the methane is stored in a liquid state similar to Liquid Natural Gas (LNG). The maximum quantity of methane that may be stored at the consumption site is the demand for seven days, since a longer time is uneconomical due to evaporation losses through the safety valves of the tanks. These tanks typically cost 170,000 $ per 15,000 gallons and would require an off load pump of 20,000 $ [81]. We will assume 200,000 dollars (in 2005) per 15,000 gallons as a typical storage cost.

We assume that LNG will be transported by electric trucks which will cost twice that of a conventional truck (see Section 3.1). The energy embodied in the fixed capital of bio-oil transport is currently 0.04 MJ t⁻¹ km⁻¹ for truck building and a similar quantity for road building. We will assume that the cost is double (0.08 MJ t⁻¹ km⁻¹) for electric trucks transporting LNG. The energy embodied in the operation of current tank trailers of 30 m³ capacity is 2.08 MJ t⁻¹ km⁻¹ [109]. The corresponding energy embodied in the operation of an electric truck is estimated by multiplying the latter quantity by the ratio between the efficiency of a diesel engine and the efficiency of an electric motor (Table 2). Ninety per cent of electric trailers are assumed to use batteries and 10% fuel cells.

The expression to estimate the energy \( e_{d} \) (J) embedded in storage and gas transport infrastructure is the following:
\[ e_{d} = e_{f} + e_{i} \]

where:

### Table 2

<table>
<thead>
<tr>
<th>Device</th>
<th>Efficiency</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline vehicle</td>
<td>0.20</td>
<td>[145]</td>
</tr>
<tr>
<td>Diesel vehicle</td>
<td>0.25</td>
<td>[145]</td>
</tr>
<tr>
<td>Internal combustion</td>
<td>0.225</td>
<td>[38]</td>
</tr>
<tr>
<td>Ship diesel engine</td>
<td>0.42¹</td>
<td>[148]</td>
</tr>
<tr>
<td>Fuel cell motor</td>
<td>0.40</td>
<td>[62]</td>
</tr>
<tr>
<td>Battery-powered motor</td>
<td>0.80</td>
<td>[48]</td>
</tr>
<tr>
<td>Overhead line electric motor</td>
<td>0.95</td>
<td>[48]</td>
</tr>
<tr>
<td>Electricity-to-hydrogen</td>
<td>0.48</td>
<td>[76]</td>
</tr>
<tr>
<td>Electricity-to-gas</td>
<td>0.40</td>
<td>[14]</td>
</tr>
<tr>
<td>Electricity-to-jet fuel</td>
<td>0.24</td>
<td>[37]</td>
</tr>
</tbody>
</table>

¹ The lowest value in the range of efficiencies given by Wiartsila [148] is used.
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Table 3
Estimated energy used for present and future transport, by sector.

<table>
<thead>
<tr>
<th>Energy end use</th>
<th>Final energy in 2014 (PJ)</th>
<th>Future final energy (PJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road</td>
<td>82,725</td>
<td>25,293</td>
</tr>
<tr>
<td>Rail</td>
<td>2195</td>
<td>1386</td>
</tr>
<tr>
<td>Shipping</td>
<td>10,383</td>
<td>27,255</td>
</tr>
<tr>
<td>Air</td>
<td>11,556</td>
<td>24,614/28,774/48,1504</td>
</tr>
<tr>
<td>Pipelines/fuel transport</td>
<td>114</td>
<td>97</td>
</tr>
<tr>
<td>Total transport</td>
<td>101,585</td>
<td>78,646 / 82,806 / 102,182</td>
</tr>
</tbody>
</table>

*- The three values correspond to the use of hydrogen, methane and jet fuel, respectively, as the main fuel for the aircrafts.

\[ e_v = \frac{p i w_l w_j (1.7 \times 10^6)}{3.79 \rho} \]

and:

\[ e_v = (e_i + e_f) d 10^{-3} \]

Here \( p \) is the price in 2005 USD per gallon (13.3), \( i \) is the inflation factor between 2005 and 2017, 3.79 the number of liters in one US gallon, \( \rho \) the LNG density (0.46 kg/l), \( w_l \) the storage capacity (kg of LNG) sufficient for one week of consumption, \( w_j \) is the mean energy intensity of the world industry (0.088 koe/USD) and 41.9 \( \times 10^6 \) is the conversion factor from koe to Joule, \( e_i, e_f \) are the respective energies embedded in road and truck fixed capital \((0.04 \times 10^6 \text{ and } 0.08 \times 10^6 J \text{t}^{-1} \text{km}^{-1}, \text{respectively})\), \( d \) is the mean distance (km) between the nearest refinery and any point of consumption (assumed to be 300 km), and \( 10^{-3} \) is the conversion factor from kg to tons.

Here:

\[ s_j = c_j \frac{54}{4h_j} \]

where \( c_j \) is the annual fuel consumption for air and marine transport (J), (see second column of Table 3). 54 is the number of weeks in one year, and \( h_j \) is the lower heat content of LNG (assumed to be \( 4.9 \times 10^7 \text{ J/kg} \)).

The final result is \( 2.9 \times 10^{17} \text{ J} \).

The annual energy required to transport the methane that is necessary to power the air and marine sectors may also be calculated with the following expression:

\[ e_m = \frac{e_v d 10^{-3} s_j}{\eta_m + 0.1 \eta_m} \]

where \( e_v \) is the energy used to transport by truck a unit of mass of methane over 1 km \((2.12 \times 10^6 J \text{t}^{-1} \text{km}^{-1})\), \( s_j \) is the mass of methane transported in one year, and \( \eta_m, \eta_{mot} \) and \( \eta_{ie} \) are the typical efficiencies of diesel, battery and fuel cell motors (see Table 2).

Here, \( s_j = c_j / h_j \), where \( c_j \) and \( h_j \) were defined above.

The final result of this calculation is \( e_m = 9.7 \times 10^{16} \text{ J} \). This figure is included in the third column of Table 3 under the concept of “Fuel Transport”.

3.7. Energy required by a 100% renewable transport system

García-Olivares [51] estimated the energy that a 100% renewable transport would use to provide similar services to the transport system of 2005. Here we make a similar calculation but using data on energy consumption of the transport sector in 2014 [68]. Unlike the old calculation, here we assume that air and marine transport will use natural gas instead of hydrogen as fuel. Natural gas is more stable than hydrogen and its storage and transport requirements are well known, therefore it is more easily utilized by current port and airport infrastructures.

Table 2 shows the efficiencies of different motors and the efficiency of gas production from electricity. Transmission losses have not been considered since we are interested in the ratio between different prime mover efficiencies and not in precise tank-to-wheel efficiencies. In the estimation of the electricity-to-gas process efficiency, the efficiency reported by Götz et al. [58] (0.55) is combined with the losses reported by Gagnon [48] when a compressed gas is transported away from the production site.

The expression used to estimate the energy consumption of a 100% renewable road transport system \( (e_{rr}) \) is the following:

\[ e_{rr} = e_i \left( \left( w_{fi} + w_{fi} + w_{em} \right) \eta_{fch} + \left( w_{fi} + w_{fi} \right) \eta_{fcl} \right) \]

where \( e_i \) is the energy consumption of the global road transport in 2014, \( w_{fi} \), \( w_{fi} \) and \( w_{em} \) are the fractions of energy consumed by battery-powered light vehicles, battery-powered heavy vehicles and battery-powered motorcycles, respectively; \( w_{fi} \) and \( w_{fi} \) are the fractions of energy consumed by fuel-cell-powered light vehicles and fuel-cell-powered heavy vehicles, respectively; \( e_i \) is the electric energy embodied in one low-heat-content energy unit of hydrogen (about 2.13); \( \eta_{fch} \) and \( \eta_{fcl} \) are the efficiencies to make useful work from internal combustion, battery and fuel cell motors, respectively.

We assume that the energy consumed by different categories of vehicles is proportional to the characteristic power of their motors. Thus, the fractions \( w_{fi}, w_{fi}, w_{em} \) and \( w_{fi}, w_{fi} \) are calculated as follows:

\[ w_{fi} = \frac{p_i}{\eta_{mot}} \]

where \( p_i \) is the fraction of commercial vehicles that have fuel cell motor (assumed to be 0.10); \( n_{2i}, n_{2i}, n_{3i}, n_{3i}, n_{amb}, n_{amb} \) and \( n_{mot} \) are the global numbers of medium-duty trucks, heavy-duty trucks, light commercial vehicles, ambulances, policy vehicles and motorcycles, respectively; \( p_i, p_i, p_i \) and \( p_i \) are the typical powers of the motor of light vehicles, medium duty trucks, heavy duty trucks and motorcycles (taken from Table B.1); and the total motor power \( p_i \) is:

\[ p_i = n_{mot} P_i + n_{i2} P_2 + n_{i3} P_3 + n_{mot} P_k \]

The number of light, heavy vehicles and motorcycles is taken from Table B.1. To estimate the number of ambulances in 2014, we assume one ambulance for each 30,000 people in developing countries (81% of world total population) and one ambulance for each 4350 people in developed countries (19% of total population). These figures correspond to data from Turkey [105] and Australia [121], respectively. The numbers of police cars are assumed to be equal to that of ambulances, and the numbers of fire engines are assumed to be negligible in comparison.

The corresponding expressions for rail transport is the following:

\[ e_{rr} = e_i \left( \eta_{fch} + \eta_{fcl} \right) \]

where \( e_i \) is the energy consumption of the global railway network in 2014; \( \eta_{fch} \) and \( \eta_{fcl} \) are the efficiencies of overhead line electric motors and diesel motors, respectively; and the factor 0.5 comes from the assumption that half of the world railway system (and locomotives) are already electrified.

The corresponding expression for marine transport is the following:

\[ e_{rr} = e_i \left( \eta_{fch} + \eta_{fcl} \right) \]

where \( e_i \) is the energy consumption of the global shipping network in
2014; and $\eta_{ee}$ is the efficiency of the electricity-to-gas process (Table 2). We have assumed that natural gas is produced from electricity and CO₂ (Sabatier process) and then used in fuel cells or directly in internal combustion engines. The efficiency of both motors is similar due to the low speed (high efficiency) of marine diesel engines. The fraction of energy consumed by other uses is negligible in comparison with marine bunkers and is not considered here.

Finally, the corresponding expression for air transport is the following:

$$e_{aa} = \frac{e_{as}}{\eta}$$

where $e_{as}$ is the energy consumption associated with global air transport in 2014, and $\eta$ is the efficiency of the electricity-to-hydrogen, electricity-to-gas, or electricity-to-jet fuel process (see Table 2), depending on the fuel that is assumed to be used by aircrafts.

The results are summarized in Table 3, which shows the energy that present and future transport would use, by sector. The energy demand if hydrogen or fuel jet were used for aircraft instead of methane is also included in Table 3.

4. Discussion and conclusions

In this study we have introduced the main current transportation modes for people and goods and their actual options for replacing the present-day fossil fuel-based transport modes with Renewable Energy modes. The costs are very sensitive to the chosen transport model that may prevail in the future. According to Section 2.1.2, a catenary-based public transport has roughly 24% cheaper running cost than a system based on private e-cars, even if only high occupation is permitted. This running cost would be even lower if a major deployment of e-bikes and light urban systems were implemented in substitution of e-cars. Given that the future scenario is uncertain, we have calculated the cost of a full replacement of the present fleet of vehicles, boats, and railroads for an equal number of electric transport units and electrified railroads. The number of aircrafts to be replaced has been assumed to be 50% of the present (2017) fleet.

An essentially electrical fleet of vehicles would need a recharging system. We have considered two scenarios for this: (i) a global system of electric charging stations placed in town streets, and (ii) the deployment of a TEV system along all the world’s roadways. In the first scenario we would typically have between 1.2 and 3.6 stations per block in cities with world and US mobility, respectively. It is a real challenge to accommodate such a high number of charging stations in any urban design scheme. However, this system would be between two and three orders of magnitude more economical than the TEV system: $7.9 \times 10^{10}$ USD and $3.3 \times 10^{16}$ J versus $5.3 \times 10^{13}$ USD and $2.2 \times 10^{19}$ J for the TEV system.

Table 4 summarizes the results of our cost estimates. The total capital cost of the new fleet of vehicles, ships, electrified trains and aircraft would be, using our assumptions, $3.9 \times 10^{13}$ USD, 88% for building the vehicle fleet, 8% for the new fleet of aircraft, 2.8% for the new fleet of ships, and 1.2% for new railroad electric infrastructure (locomotives and catenaries). The addition of recharging stations and gas transport infrastructure would not visibly change these results.

For reference, gross world product was $74 \times 10^{12}$ USD in 2016 (US dollars of year 1990) in 2016 [71], which is equivalent to $13.6 \times 10^{13}$ USD in 2016 (dollars of 2016). Thus, the new infrastructure would cost 33% of the world product of 2016. If this is to be accomplished within 30 years, the rate of investment should be 1.1% of gross world product per year following the hypotheses we have proposed in this study. Given that world capital formation is about 25% of gross world product [71], such an investment seems achievable, even though it would have to be accompanied by a similar investment in renewable energy production infrastructure.

However, if a TEV system were chosen, its capital investment would be $5.3 \times 10^{13}$ USD, higher than the investment in renewal of transport fleets alone. In this case, the total investment would be $9.8 \times 10^{13}$ USD and the rate of investment should be 2.2% of gross world product per year.

Global transport infrastructure investment between 2014 and 2025 has been projected to be $14 \times 10^{12}$ USD [104], equivalent to $1.4 \times 10^{15}$ USD per year as an average for the coming years. On the other hand, global output for vehicles manufacturing was 66 million vehicles and almost $2 \times 10^{12}$ euros of gross turnover in 2005 [101]. In 2016, global production of vehicles was 95 million [102]. Thus, if vehicle turnover rate has been approximately maintained, global turnover should currently be about $2.9 \times 10^{12}$ euros or 3.5 $\times 10^{12}$ USD per year. This figure may be considered equal to annual expenditure on new vehicles. If the transition takes place within 30 years, its annual cost for vehicle fleet renewal would be 34% of current annual expenditures on new vehicles. Thus, this replacement is feasible and can be considered as a part of the usual renewal of the transport fleet. On the other hand, annual infrastructure investment in gas storage and recharging points or a TEV system would amount to 0.4% and 126% of the present transport infrastructure investment if the recharging posts and TEV system were used, respectively. Thus, a global electrification of the road network would demand an additional investment effort of 40% over current levels.

In the short term, scenario (i) (recharging posts) has the appeal of a reduced cost but it may maintain or even increase car overcrowding in our cities and, in the long term, may cause a strong price increase of the nickel and lithium minerals used in car batteries. The scenario (ii) would avoid these problems by making smaller car batteries possible and making recharging points in towns and cities unnecessary, albeit at a very high cost. A third alternative that would avoid congestion problems in cities and high capital investments is car sharing. This is a system for renting a car for short periods of time (as short as one hour) that avoids the necessity of car ownership and that could reduce the passenger car fleet by the order of 69%, increasing the average time of use for every car. In addition, it would maximize the use of battery cycles. This kind of system is apparently well adapted to the decrease of purchasing power of the middle classes that has been observed in developed countries since 2008, and to the relatively high prices of present-day electric cars.

In scenario (i), the embodied energy required for the transport
transition is 16,415 PJ, 91% for vehicles, 2.4% for airplanes, 2.9% for boats, 1.2% for electrification of railways, 1.8% for gas storage and 0.2% for recharging posts. This amounts to 4.2% of the secondary energy (at the consumption points) produced in 2014 [68] and to 16% of the secondary energy consumed by the transport sector in 2014. If the transition were to occur within 30 years, the energy investment would be about 0.1% of the total secondary energy per year (0.5% the energy consumed by transport per year). In scenario (ii), these figures would be 9.7% of the secondary energy of 2014 and an investment of 0.3% of secondary energy of 2014 per year.

Our estimate does not consider new infrastructure requirements for electricity-to-gas powering of the system. The transition should also be accompanied by new infrastructure for renewable energy production, backup, and smart grids to interconnect electrical production, storage and consumption sites. The capital and energy investments required for the new infrastructure needed for a 100% renewable economy will be studied elsewhere. However, the fact that the energy embodied in the fixed capital of transport infrastructure is only a minor fraction of the secondary energy used annually by the economy suggests that the new infrastructure will not be the main part of the problem in a 100% renewable transition.

As Table 3 shows, a 100% renewable transport system that delivers the same service as world transport in 2014 would demand about 18% less energy. The main reduction is expected in road transport (69%) due to the larger efficiency of battery power in relation to internal combustion, and the limited number of fuel cell vehicles, which have been assumed to consist only of ambulances, police vehicles, and 10% of commercial vehicles. The numbers of fuel cells in road transport should be limited due to the need to allocate the fuel cells for special vehicles, marine transport, and even the maintenance of sufficient reserves of platinum and palladium for other industrial uses [51].

In contrast, the shipping and air sectors would notably increase their consumptions: 163% and 149%, respectively. This is derived from the need to produce natural gas from electricity in order to power the engines of planes and boats. This suggests strong price increases of both kinds of services, and decrease in intercontinental transport. This may produce some relocation of economic activity. The use of hydrogen to fuel aircrafts instead of methane would save some energy, although at the cost of higher safety concerns. On the other hand, the use of jet fuel would increase air sector consumption by 317% in relation to its present consumption and would make this sector consume 47% of the total transport sector energy demand (Table 3). This would have a dramatic and, probably, unbearable effect on prices and air mobility.

To maintain the prices of flights at similar level to that of today, the ratio of energy consumed by the air sector in relation to the total energy available should be similar to the one in the present economy, about 3% [68]. A future 100% RE economy able to offer the same service as a contemporary fossil economy would demand about 87% the energy of the latter [51]; this would amount to 342,110 PJ of secondary energy consumed by the transport sector in 2014. If the transition were to occur within 30 years, the energy investment would be about 0.1% of the total secondary energy per year (0.5% the energy consumed by transport per year). In scenario (ii), these figures would be 9.7% of the secondary energy of 2014 and an investment of 0.3% of secondary energy of 2014 per year.

The transition to 100% renewable air and maritime transport would not entail any energy or monetary savings compared to the current system. Therefore, from a perspective of economic rationality, the substitution of fossil fuels in transportation should begin with land transport – where it would save a greater amount of energy and CO₂ at lower cost – and leave the complete renewable conversion of the two former sectors until later.

Markets are increasingly investing in renewable production and transportation, but not to the rate required to avoid irreversible climate change [123]. The necessary profound technological change and implementation investments required for transport electrification suggests that a decisive effort should be focused towards the political/practical arena of governments. This poses immediate challenges, in part pointed out here, which may require decisive policies and new approaches to achieve the projected aims for supporting transport system decarbonization.

The main material constraints that may put a large-scale development of onboard batteries, electric motors, fuel cells and renewable aircrafts in danger are: limited reserves of lithium and nickel, limited copper reserves, use of rare metals such as platinum and palladium in fuel cells, and high energy costs of synthesizing aircraft fuels from electricity.

According to this study, a set of measures to anticipate these risks is recommended and should be supported and fostered by governments and civil society:

- Substitution of most of the current inter-urban land transport, which is based on trucks and private cars, by electric trains for freight and passengers.
- Use of EVs only for short-distance transport between cities with no public transport alternative.
- Limited use of EVs, which translates into a relatively small fleet. The same size as present could be considered an upper limit, but it would not solve congestion problems in cities, could increase prices of important metals such as Ni and Li, and could put in danger their availability for other industrial uses. Priority should be given to electrified public transport.
- Use of fuel cells only when autonomy and power requirements of the vehicle demand it.
- Reduction of aviation fleets in favour of (i) rail systems and (ii) marine transport, in this order.
- Reorganization and reduction of marine traffic, as cargo vessels are major consumers of fuels (as of present) and hydrogen and biogas fuel cells (in the future).
- Optimization of logistics and work, in order to reduce travel demand.
- Shifting transport ‘modes’ from high to low energy intensity. Appropriate parameters to quantify this intensity and prioritization modes would be kWh per passenger-km and kW h per Tm-km.
- Improvement of energy efficiency not only by using the best technologies available but also by acting on urban and public transport infrastructures. Fostering of TaaS (Transport as a Service) and car-sharing have great potential to decrease demand for energy and materials for road transport.

Some of the limitations of the present analysis include the uncertainty, unpredictability or difficulty of projecting the following factors:

- Break-through technologies that might replace critical resources or alleviate the energetic deficit.
- Evolution of population distribution and migrations forced by climate change and future wars.
- Evolution of economic inequality, which could hamper renewable investment in many countries.
- Political and market decisions fostering specific pathways of transition of the current fossil fuel transport to electric transport. Readiness and global states’ consensus on deployment of a decarbonized economy, which can translate into different scenarios for how the transition is financed and fostered.
- Economic resources available in future scenarios of climatic and environmental crises.

Another conclusion of this study is that a renewable transport system is feasible but not necessarily compatible with the usual exponential growth of resource consumption. We are entering an age where the investments required in the next few decades will involve the use of large fractions of the reserves of important metals such as Cu, Ni, Li, Pt and Pa. Some of these metals (e.g. Pt and Pa) have specific physical properties that make them essential. Therefore, any policy for the necessary renewable transition may no longer be based exclusively on prices and incentives, but must also consider geological reserves and material scarcity. In the next 50 years, the lack of elasticity of metal reserves will probably hasten the necessity for designing of a post-capitalist economy which will use new economical tools. Some of these tools would be the use of geophysical and sustainability indicators, abandonment of GDP as the main indicator of economic success, incorporation in the economy of long-term planning and scientific environmental assessment and, most importantly, introduction of new mechanisms which may create prosperity without necessarily increasing the consumption of resources and materials.

Acknowledgments

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Appendix A

Here we estimate the mean energy density during the period of transition between the 2014 economy and a 100% renewable economy. We will assume that new electricity added to that produced globally in 2014 grows at the rate observed in 2015: 8.3% [75] over the full period.

The following expression is used for the new renewable electric contribution to the transport equipment industry after 2014:

\[
pe(t) = pt14 + wmt[pf14 \times 0.083(t-2014)] - pt14
\] (A.1)

Here \(pe\) is the annual secondary energy from new electricity (relative to 2014) consumed by the transport equipment industry; \(pt14\) is the electricity produced from new renewables in 2014, about 20% of 69 EJ ([74,75], Figura 13); \(pf14\) is the electricity consumed by the transport equipment industry in 2014 (988 PJ according to [68]); \(wmt\) is the weight of the energy consumption of the transport equipment industry relative to the total final energy in the economy of 2014 (0.005, see [68]).

At this rate, the electricity available for the sector reaches \(pe = 0.87 pt14\) by the year 2043 (Eq. (A.1)). This is only a heuristic exercise for purposes of calculation; in reality, economic growth will demand a higher rate of energy production. The World Energy Council ([151], see Fig. 37) projects a final energy demand of 490 EJ globally in the year 2050 in its scenario « Symphony » of moderate growth, which is 1.32 times higher than the secondary energy produced in 2014 [69]. To satisfy this demand with renewables would take until 2050 at the abovementioned rate of deployment, according to Eq. (A.1).

The fossil fuel contribution must decrease slowly at the beginning and at an increasing decommissioning rate sufficient to maintain a monotonic decrease of \(pt(t)\) between \(pt14\) and the final energy production that is able to maintain similar levels of service: \(pt = 0.87 pt14\). The following parabolic curve, with \(a = 1.78\), satisfies these conditions:

\[
ptf(t) = \frac{pt14}{(2042.5-2014)^{a}} (t-2014)^{a}
\]

Here \(ptf\) is the annual secondary energy from non-electric carriers consumed by the transport equipment industry.

The energy consumed by the sector, normalized by the 2014 value, is given by the following expression:

\[
pst(t) = \frac{pt(t) + ptf(t)}{pt(2014)}
\]

This function (Fig. 1) shows the relative decrease of the energy density between 2014 and year 2042.8. With these assumptions, a unit of energy density of 2014 would decrease to 0.87 by year 2042.8 following the curve displayed in Fig. 1.
The mean value of this curve along the period is its area divided by (2042.8–2014), which amounts to 0.93. A simpler but less realistic model for the decrease of $p_{\text{tm}}(t)$, for instance, a linear decrease between 1 and 0.86, leads to the same value, 0.93. Therefore, for the present, all the energy densities calculated are multiplied by this factor to project the mean energy density during the transition period. This figure is slightly conservative, since the expected production growth would give a higher weight to the second half of the period which tends to decrease the mean value.

Appendix B

Table B1
Classes of vehicles (column 1), global number in 2015 (column 2), typical peak power of its battery if it were electric (column 3), battery capacity (column 4) and typical price of the electric version.

<table>
<thead>
<tr>
<th>Kind of vehicle</th>
<th>Number in 2015 (millions)</th>
<th>Power (KW)</th>
<th>Battery capacity (KWh)</th>
<th>Typical price (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light duty vehicles</td>
<td>1117(^a)</td>
<td>60</td>
<td>22.4</td>
<td>22,000</td>
</tr>
<tr>
<td>Medium freight trucks(^b)</td>
<td>32(^c)</td>
<td>179</td>
<td>120</td>
<td>100,000</td>
</tr>
<tr>
<td>High Freight Trucks(^d)</td>
<td>24(^f)</td>
<td>339</td>
<td>700(^e)</td>
<td>284,000(^g)</td>
</tr>
<tr>
<td>Two-three wheelers</td>
<td>669(^a)</td>
<td>3.6</td>
<td>1.2</td>
<td>5500</td>
</tr>
</tbody>
</table>

\(^a\) From IEA [69]. The number includes 130 million light commercial vehicles [70].
\(^b\) Trucks from 7.5 to 16 tons. The reference electric truck is the EMOSS EMS 10 with 10 Tm gross vehicle weight [40].
\(^c\) From IEA [70].
\(^d\) Trucks heavier than 16 tons.
\(^e\) Twice the price of the tractor unit Volvo D13 EcoTor with 455 HP [54].
\(^f\) Maximum battery capacity of an electric vehicle in 2017 [107]; the figure is given as a reference but is not used in our calculations.

Table B2
Values used for the estimation of metals required by the transport system. Density refers to the mass of metal used per unit of power or per unit of energy stored in engine, battery or fuel-cell. The parameters used were discussed in García-Olivares et al. [50]. The reserves were estimated by the US Geological Survey [144].

<table>
<thead>
<tr>
<th>Metal</th>
<th>Density (kg/kW or kg/kWh)</th>
<th>Reserves (10^6 t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>0.73</td>
<td>720</td>
</tr>
<tr>
<td>Lithium</td>
<td>0.3</td>
<td>14</td>
</tr>
<tr>
<td>Nickel</td>
<td>2.5</td>
<td>79</td>
</tr>
<tr>
<td>Platinum</td>
<td>0.004</td>
<td>0.015 (0.07(^f))</td>
</tr>
</tbody>
</table>

\(^a\) Reserves of Pt group metals (Pt, Pd, Rh, Ru, Ir, Os).
Appendix C

The main kind of current merchant ships are: bulk carriers, general cargo ships, crude oil tankers, container ships, chemical tankers, passenger ships, and liquefied natural gas tankers. Fishing vessels are also considered in order to complement the calculation.

The number of bulk carriers was 16,916 ships in 2015. The fractions of different classes within bulk carriers and the approximate price (in $USD2010) of a new ship of the corresponding class (Handysize, Handymax, Panamax, Capesize) are shown in Table C.1.

The fractions are taken from Lamb [83] and the approximate price is a mean figure from an Internet search of shipping companies. Error in the mean prices is assumed to be larger than the inflation between 2010 and 2016.

The aggregate price of the new fleet of bulk carriers is estimated using:

\[ p_{\text{fl}} = n_b (f_1 p_1 + f_2 p_2 + f_3 p_3 + f_4 p_4) \]

where \( n_b \) is the number of bulk carriers, \( f_1 \) to \( f_4 \) are the fractions given in the second column of Table C.1, and \( p_1 \) to \( p_4 \) are the prices given in the third column of Table C.1.

The result is \( 5.11 \times 10^{11} \) USD.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Energy intensity Koe per $USD2005</th>
<th>Energy intensity Koe per $USD2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>USA</td>
<td>0.09</td>
<td>0.072</td>
</tr>
<tr>
<td>Japan</td>
<td>0.09</td>
<td>0.072</td>
</tr>
<tr>
<td>Germany</td>
<td>0.07</td>
<td>0.056</td>
</tr>
<tr>
<td>South Korea</td>
<td>0.12</td>
<td>0.096</td>
</tr>
<tr>
<td>India</td>
<td>0.12</td>
<td>0.096</td>
</tr>
<tr>
<td>Mexico</td>
<td>0.06</td>
<td>0.048</td>
</tr>
<tr>
<td>Spain</td>
<td>0.08</td>
<td>0.064</td>
</tr>
<tr>
<td>Brasil</td>
<td>0.16</td>
<td>0.128</td>
</tr>
<tr>
<td>Canada</td>
<td>0.14</td>
<td>0.112</td>
</tr>
<tr>
<td>France</td>
<td>0.08</td>
<td>0.064</td>
</tr>
<tr>
<td>Thailand</td>
<td>0.13</td>
<td>0.104</td>
</tr>
<tr>
<td>UK</td>
<td>0.06</td>
<td>0.048</td>
</tr>
<tr>
<td>Russia</td>
<td>0.23</td>
<td>0.184</td>
</tr>
<tr>
<td>Turkey</td>
<td>0.08</td>
<td>0.064</td>
</tr>
<tr>
<td>Czech Rep.</td>
<td>0.08</td>
<td>0.064</td>
</tr>
<tr>
<td>Indonesia</td>
<td>0.04</td>
<td>0.032</td>
</tr>
<tr>
<td>Italy</td>
<td>0.08</td>
<td>0.064</td>
</tr>
<tr>
<td>Slovakia</td>
<td>0.10</td>
<td>0.080</td>
</tr>
<tr>
<td>Iran</td>
<td>0.12</td>
<td>0.096</td>
</tr>
<tr>
<td>Poland</td>
<td>0.06</td>
<td>0.048</td>
</tr>
<tr>
<td>South Africa</td>
<td>0.18</td>
<td>0.144</td>
</tr>
<tr>
<td>Malaysia</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Argentina</td>
<td>0.07</td>
<td>0.056</td>
</tr>
<tr>
<td>Hungary</td>
<td>0.08</td>
<td>0.064</td>
</tr>
<tr>
<td>Belgium</td>
<td>0.12</td>
<td>0.096</td>
</tr>
<tr>
<td>Romania</td>
<td>0.08</td>
<td>0.064</td>
</tr>
<tr>
<td>Taiwan</td>
<td>0.08</td>
<td>0.064</td>
</tr>
<tr>
<td>Sweden</td>
<td>0.14</td>
<td>0.112</td>
</tr>
<tr>
<td>Uzbekistan</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Australia</td>
<td>0.12</td>
<td>0.096</td>
</tr>
<tr>
<td>Portugal</td>
<td>0.11</td>
<td>0.088</td>
</tr>
<tr>
<td>Slovenia</td>
<td>0.08</td>
<td>0.064</td>
</tr>
<tr>
<td>Austria</td>
<td>0.09</td>
<td>0.072</td>
</tr>
<tr>
<td>Serbia</td>
<td>0.10</td>
<td>0.080</td>
</tr>
<tr>
<td>Finland</td>
<td>0.24</td>
<td>0.192</td>
</tr>
<tr>
<td>Netherlands</td>
<td>0.10</td>
<td>0.080</td>
</tr>
<tr>
<td>Egypt</td>
<td>0.06</td>
<td>0.048</td>
</tr>
<tr>
<td>Ukraine</td>
<td>0.24</td>
<td>0.192</td>
</tr>
<tr>
<td>Norway</td>
<td>0.08</td>
<td>0.064</td>
</tr>
<tr>
<td>Croatia</td>
<td>0.07</td>
<td>0.056</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>0.08</td>
<td>0.064</td>
</tr>
<tr>
<td>World</td>
<td>0.11</td>
<td>0.088</td>
</tr>
</tbody>
</table>

Table C1

Fractions and prices of bulk carriers in 2010 US dollars.

<table>
<thead>
<tr>
<th>Carrier</th>
<th>Fraction</th>
<th>Price, $10^6</th>
<th>$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handysize</td>
<td>0.34</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Handymax</td>
<td>0.37</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Panamax</td>
<td>0.19</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Capesize</td>
<td>0.10</td>
<td>58</td>
<td></td>
</tr>
</tbody>
</table>
General cargo ships are about 10,696. According to Statista the 2015 overall fleet had a capacity of $77 \times 10^6$ dwt (tons of dead weight). Thus, the capacity of an average vessel is about 7199 t, and the price of a general cargo ship of 7200 t dwt is currently about $10 \times 10^6$ USD. Thus, the cost of the new global cargo fleet would be about $1.07 \times 10^{11}$ USD.

Crude oil tankers will no longer be necessary in a post-carbon economy and thus are not considered in this calculation. We suppose here that they will be progressively decommissioned as global decarbonization proceeds. However, in our calculations the costs of decommissioning and (use/recycling) of such vessels are not considered.

The price of container ships ($p_{cs}$) is estimated as a function of its TEU (Twenty-Foot Equivalent Unit) number with the following expression:

$$p_{cs}(t_{eu}) = 12.68 \text{teu}^{0.63}$$

which is obtained from the following three conditions:

(i) $p_{cs}(4000) = 60 \times 10^6$; (ii) $p_{cs}(12,000) = 120 \times 10^6$; and (iii) $p_{cs}$ follows a potential law with size [98].

The total number of container ships is about 5000, and we will consider the classes of container ships shown in Table C2 [129].

The aggregate price of the new container ship fleet is estimated with the following expression:

$$p_{cs} = \sum_{j=1}^{12} f_j p_{cs} (d_j)$$

where $f_j$ are the fractions shown in column 4 of Table C2, and $d_j$ are the mean values of the ranges shown in column 1 of the same Table.

The result is: $2.75 \times 10^{11}$ USD.

The number of chemical tankers is about 4999, with a capacity of $75 \times 10^6$ dwt in 2015 [22], which implies a mean capacity of 15,003 dwt per vessel. According to Epca [41] the cost of a chemical tanker is 2–3 times that of an oil tanker of similar size. Taking 2.5 as an appropriate factor and considering the approximate price of an oil tanker, 500 $/dwt up to 80,000 t, we obtain a price for the new chemical fleet of $9.38 \times 10^{10}$ USD.

The number of passenger ships is about 4066. In average, cruises have an approximate capacity for 1630 passengers; there are only 298 large ships [28], and their building cost is about $500 \times 10^6$ $ for a medium size ship [59]. We assume that the remainder of the ships are medium size ferries of about 62 passenger-cars equivalent and 1.3 million USD of capital cost [78]. The aggregate price of the new fleet of passenger vessels ($p_{ps}$) is estimated with the expression:

$$p_{ps} = n_1 p_1 + n_2 p_2$$

<table>
<thead>
<tr>
<th>Carrier capacity, TEU</th>
<th>Carrier class</th>
<th>Amount</th>
<th>Fraction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>18,000-20,000</td>
<td>Ultra large container vessel</td>
<td>35</td>
<td>0.6</td>
</tr>
<tr>
<td>13,300-17,999</td>
<td>Ultra large container vessel</td>
<td>109</td>
<td>2.1</td>
</tr>
<tr>
<td>10,000-13,299</td>
<td>New panamax</td>
<td>193</td>
<td>3.7</td>
</tr>
<tr>
<td>7500-9999</td>
<td>Post-panamax</td>
<td>454</td>
<td>8.8</td>
</tr>
<tr>
<td>5100-7499</td>
<td>Post-panamax</td>
<td>510</td>
<td>9.9</td>
</tr>
<tr>
<td>4000-5099</td>
<td>Panamax</td>
<td>735</td>
<td>14.3</td>
</tr>
<tr>
<td>3000-3999</td>
<td>Panamax</td>
<td>262</td>
<td>5.1</td>
</tr>
<tr>
<td>2000-2999</td>
<td>Feedermax</td>
<td>648</td>
<td>12.6</td>
</tr>
<tr>
<td>1500-1999</td>
<td>Feeder</td>
<td>581</td>
<td>11.3</td>
</tr>
<tr>
<td>1000-1499</td>
<td>Feeder</td>
<td>696</td>
<td>13.5</td>
</tr>
<tr>
<td>500-999</td>
<td>Small feeder</td>
<td>748</td>
<td>14.5</td>
</tr>
<tr>
<td>100-499</td>
<td>Small feeder</td>
<td>182</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Table C2

Fractions of container ships in 2015 by TEU.

<table>
<thead>
<tr>
<th>Exporter</th>
<th>Export value (2016 USD million)</th>
<th>Share in world export %</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>523,251</td>
<td>100</td>
</tr>
<tr>
<td>Rep. of Korea</td>
<td>145,774</td>
<td>28</td>
</tr>
<tr>
<td>China</td>
<td>105,212</td>
<td>20</td>
</tr>
<tr>
<td>Japan</td>
<td>52,599</td>
<td>10</td>
</tr>
<tr>
<td>Germany</td>
<td>21,305</td>
<td>4</td>
</tr>
<tr>
<td>Poland</td>
<td>20,233</td>
<td>4</td>
</tr>
<tr>
<td>Brazil</td>
<td>15,928</td>
<td>3</td>
</tr>
<tr>
<td>India</td>
<td>15,440</td>
<td>3</td>
</tr>
<tr>
<td>Italy</td>
<td>15,277</td>
<td>3</td>
</tr>
<tr>
<td>Netherlands</td>
<td>12,508</td>
<td>2.4</td>
</tr>
<tr>
<td>USA</td>
<td>11,553</td>
<td>2.2</td>
</tr>
<tr>
<td>France</td>
<td>8140</td>
<td>1.6</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>6961</td>
<td>1.3</td>
</tr>
<tr>
<td>UK</td>
<td>6344</td>
<td>1.2</td>
</tr>
<tr>
<td>Singapore</td>
<td>6123</td>
<td>1.1</td>
</tr>
<tr>
<td>Others</td>
<td>79,854</td>
<td>15.2</td>
</tr>
</tbody>
</table>

Table C3

Export value and share in world export of the main floating structure exporters (from [142]).
where $n_1$, $n_2$ are the number of the two kind of passenger ships under consideration, and $p_1$, $p_2$ are their respective prices.

The result is: $1.5 \times 10^{11}$ USD.

Liquified natural gas tankers will continue to exist due to the necessary use of methane (of renewable origin) in marine and air transport, and for industrial use in a future post-carbon economy. However their number is currently 1677, and this will probably be much less in the future; for this reason these are not be considered in this calculation.

In 2012 there were $n_f = 4.72 \times 10^6$ fishing vessels, 57% engine-powered and 43% unpowered, 79% smaller than 12 m, and 64,000 larger than 24 m [42]. It follows that 36% are smaller than 12 m with motors, 64,000 ships are larger than 24 m and $(21/100)$ $4.72 \times 10^6$ less 64,000 are between 12 and 24 m.

These prices are taken from an average eyeball estimation of market prices for online motor boats built in 2016 in the respective length bands. The numbers and typical prices of the three fractions are the following:

Number of ships larger than 24 m: $n_{f3} = 64,000$.

Typical price of this class (USD): $p_3 = 3. \times 10^6$

Number of engine-powered ships smaller than 12 m: $n_{f1} = 0.36 n_f$

Typical price of this class (USD): $p_1 = 100,000$.

Number of ships between 12 and 24 m: $n_{f2} = (21/100) n_f - n_{f3}$

Typical price of this class (USD): $p_2 = 1.6 \times 10^6$.

And the total aggregate price of the future fishing fleet is estimated using the following expression:

$$p_f = n_{f1} p_1 + n_{f2} p_2 + n_{f3} p_3$$

The result is: $1.85 \times 10^{12}$ USD.

### Appendix D

#### Table D1

<table>
<thead>
<tr>
<th>Type of aircraft</th>
<th>Examples</th>
<th>Mean price 10^6 USD of 2016</th>
<th>Percentage</th>
<th>Number in 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small freighter</td>
<td>AN-32</td>
<td>15</td>
<td>1.6</td>
<td>408</td>
</tr>
<tr>
<td>Medium freighter</td>
<td>A330-200F</td>
<td>235</td>
<td>3.4</td>
<td>884</td>
</tr>
<tr>
<td>Large freighter</td>
<td>Beluga, A380-F, B747-200F, B747-400F</td>
<td>262</td>
<td>2.6</td>
<td>680</td>
</tr>
<tr>
<td>Regional &lt; 100 seats</td>
<td>E-170, E-175, E-190, MRJ-70, MRJ-90</td>
<td>45</td>
<td>5.7</td>
<td>1495</td>
</tr>
<tr>
<td>Narrowbody 100–210 seats</td>
<td>A320, B737-800</td>
<td>94</td>
<td>65.9</td>
<td>17,196</td>
</tr>
<tr>
<td>Intermediate widebody</td>
<td>A330, A350, B767</td>
<td>269</td>
<td>15.6</td>
<td>4078</td>
</tr>
<tr>
<td>Large widebody</td>
<td>B747, B777, A380</td>
<td>304</td>
<td>5.2</td>
<td>1359</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>26,100</td>
</tr>
</tbody>
</table>

#### References


[17] Choo S, Mokhtarian PL, Salomon I. Does telecommuting reduce vehicle-miles...


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Oleg Osychenko. Qualification: Degree and PhD in Physics.

Main specialization in Physical oceanography, numerical modelling and energy policy.