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Transportation in a 100% renewable energy system

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ABSTRACT

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 [77,50,72,125,86,27,123,15]. 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 Ballabrera [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

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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 TWa/a. 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 LCE-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 proven 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