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Review

A Review on Energy Efficiency in Three Transportation Sectors: Railways, Electrical Vehicles and Marine

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Received: 15 March 2020; Accepted: 8 May 2020; Published: 9 May 2020

Abstract: The present paper is a review on efficiency issues related to three important sectors of the transportation systems: railways, electrical vehicles, and marine. For the three sectors, the authors, in reference of their knowledge and research area, show the results of a wide literature analysis, in order to highlight which are the measures, in terms of technological solutions and management techniques, which are recently investigated and implemented, for improving the three transportation systems, from the point of view of efficiency. In particular, for the railway transportation sector, a wide analysis is presented, detecting which are the main measures adopted for improving the efficiency, related to the power systems for supplying trains and to the train traffic control, with a focus on the storage system integration. For electric road vehicles the analysis is focused on the plug-in electrical vehicles and on the infrastructure for their recharge, with an emphasis on how these vehicles can support the grid, e.g., through Vehicle to Grid (V2G) applications. Finally, for the marine transport service the review is related to the propulsion systems and on how the different solutions can meet the objective of efficiency.

Keywords: electrical transport; electrical vehicle; energy efficiency; marine transport; railway

1. Introduction

The guideline suggested by European Commission in 2008 about climate and energy, in a horizon 20-20 context, focuses on the reducing the greenhouse gas (GHG) emissions and increasing the production from renewable energy sources (RES) [1]. The main aspect taken into account, among the first goals reported in [2,3], is the electrification of the transport sector [4].

Nowadays, the current world population of 7.3 billion is expected to reach 8.5 billion by 2030, so the mobility demand for people and goods has already grown in many countries, and it will keep growing, with heavy environmental impacts [5].

From this point of view energy savings solution will be increasingly necessary in order to reduce more and more the energy demand required by the transport systems for the next future. However, energy efficiency has been already increased in the last century thanks to the many technological innovations that have occurred over time in the transport sector [6].

The present paper is a review on efficiency issues related to three important sectors of the transportation systems: railways, electrical vehicles (EVs), i.e., cars, and marine. For the three sectors, the authors, in reference to their knowledge and research area, show the results of a wide literature analysis, in order to highlight which are the measures, in terms of technological solutions and management techniques, which are recently investigated and implemented, for improving the three transportation systems from the point of view of the efficiency, in reference to their peculiarities.

In reference to the railway sector, considering that most of the rail-lines are electrified and use electric trains, the review deals with the measures that can be adopted for improving the efficiency of existing electrical systems, especially in reference to the electrical infrastructure for the supply of the trains and to the management of the train traffic. A focus is reported also on the recent measure of integration of storage systems in the railways system, as action in the direction of efficiency improvement.

In reference to the on-road vehicles the analysis is focused on the plug-in electrical vehicles and on the infrastructure for their recharge, with a focus on how these vehicles can support the grid, e.g., through Vehicle to Grid (V2G) applications.

In reference to the marine transport, the review is related to the propulsion systems and to how the different solutions can meet the objective of efficiency.

It is worth stressing that the final objective is not to find a common metric for the assessment of the efficiency and its improvement in relationship to the different solutions, but to find differences and to cluster the possible measures that can be applied to the three transport sectors for improving the efficiency, in terms of the functions of their peculiarities. It gives an idea of what has been already done and which could be the margin of development to be explored.

This paper is organized in three parts, each dedicated to the single transportation systems investigated.

2. Efficiency in Railway Transportation Sector

Railways are an energy efficient mode of transport for both passengers and freight. Passenger railways cover an average value of 4.1 of toe per million passenger-km; the freights rails cover an average value of 3.49 of toe per million passenger-km. It represents 2% of total transport energy demand [7]. The construction of new railway lines, as the growing of the number of trains on the lines increases, imposes that energy savings solutions are increasingly necessary to reduce the energy demand in the future, considering both urban and suburban systems.

Energy efficiency has already improved in the last century thanks to the many technological innovations that have occurred over time in the railway sector: from the first storage systems on board trains (1903) to cover short distances, until today with the development of different types of electrified lines both DC and AC (single and three-phase). The development of high efficiency electric engines and the increasing progress in power electronics allowed reducing the energy demand by trains, also thanks to braking energy recovery utilization. In electrical substation, from the '60s to today, the replacement of mercury vapours rectifiers with silicon rectifying diodes in DC electrical substations, and the continuous introduction of high performance electric machines for energy conversion, minimizing the losses, have increased the efficiency of the systems. A continuous evolution concerned also the better integration between train and infrastructure (pantograph/overhead lines and wheels/rails). Evaluations about energy recovery, centred on the control of speed profile, taking into account timetable optimization [8–10] and storage design systems [11], offer a best solution to reduce the system's energy consumption, in order to maximize the effectiveness of regenerative braking. The importance of increasing recovering energy, especially when there is no train that can absorb it, or it is not possible to install a reversible substation, is also discussed [11]. Several solutions have been carried out focusing on trains, power plant design and timetable optimization, in order to decrease the energy dissipated on braking rheostat. Regarding the trains driving performance, many solutions are proposed to optimize driving style management and the design of super-caps on board. Several design solutions have been carried out for the siting and sizing of storage systems in railways power plant and at last, some proposal about optimal scheduling process have been formulated for timetable management.

The results of a wide survey on the newest techniques of driving style management with timetable optimization and on the solution of storage systems on board and stationary is summarized in the next paragraph.

2.1. Efficiency Solutions Based on the Driving Style Management and Timetable Optimization

Energy-efficient driving management coupled with the optimization of timetable allows finding optimal train speed profiles and departures to minimize the energy consumption and get the optimal braking trend due to time delay, so as to maximize the recoverable energy in line. Researches start from 1960, with timetable optimization and energy-efficient driving from the first suggested optimal control model in 1968 made by Ishikawa [10].

Several timetable optimization methods have been proposed in recent years [10]. Albrecht in [12] developed a new method based on dynamic programming, to manage running time of trains using an optimal combination of headway and synchronization time, with the task of reducing power peaks and energy consumption. Chen et al. [13] applied the genetic algorithm to optimize train scheduling; particularly the goal was to reduce power consumptions, preventing the synchronous acceleration of many trains. Ramos et al. [14] presented a method to maximize the braking energy recovery, during off-peak hours maximizing the overlapping time between acceleration and braking of the trains. Kim et al. [15] carried out a multi-criteria mixed integer programming, coordinating the train departure times at the starting stations, so as to minimize the peak energy and maximize regenerative energy utilization. Peña-Alcaraz et al. in [16] tested methods to synchronize the movement of trains in the Madrid Metro Line 3 reaching a 3.52% energy saving. In [17,18] a comparison between to real metro-lines in Italy and Spain is made in terms of energy savings that can be obtained by the recovering of the braking energy of the trains. Yang et al. with several studies suggested a cooperative scheduling model to schedule the accelerating and braking phases of nearby trains. In [19] a simulation performed on real data obtained from the Beijing Metro Yizhuang Line shows a great improvement in the overlapping time of around 22%. In [20] a stochastic cooperative scheduling model taking into consideration the randomness of departure delay, for trains considering busy stations, shows a percentage of save energy around 8%, compared with the cooperative scheduling approach reported in [19]. In [21] the same authors offer a model to optimize the timetable, coordinating trains at the same station to maximize the utilisation of recovery energy and reduce waiting time for the passengers. The model reached an 8.86% energy saving, with a waiting time of 3.22% relevant to the current timetable. In [22] a scheduling approach regarding effective speed profiles, to arrange arrivals and departures of all trains, reaches a 6.97% reduction in energy consumption, in comparison with the current timetable.

In [23] a model, based on a multidimensional state vector subspace for train operation, is presented. A smart scheduling methodology useful for multi-train energy saving operation and an optimization procedure based on a genetic algorithm and regenerative kinetic energy, to lowest total energy consumption, is proposed in [23,24].

In [25] the train trajectory optimization is carried out, in order to define a better train target speed profile, to minimize a cost function, including energy consumption and trains arriving on time for all trains. The minimum energy consumption, under different departure headways, is calculated, by using a heuristic algorithm in [26], reaching a reduction in energy consumption up to 19.2%. Furthermore, several studies on driving style are carried out, to define eco-energy driving profile strategies of the trains to couple with timetable optimisation. The motion stage of a train consists in acceleration, cruising, coasting, and braking management. Generally, the speed profile of trains with short travel distance or close intermediate stops, like in tram and metro systems, could not contain the cruising phase.

In [27] a dual speed-curve optimization for energy-saving operation of high-speed trains is proposed using two optimizations. An offline global and online local optimization, demonstrating the increase in energy saving, compared with other well know existing methods that use one-time optimization processes. The main structures of the dual optimization method proposed include: a global optimization to obtain better driving style; after, the speed trajectory is adjusted in real time by local optimization. Additionally, regarding rolling optimization, a closed loop control is integrated with a consistent optimization process that continuously corrects; at least global optimization is reachable using a genetic algorithm, with characteristics and predictive control, with the local optimization characteristics, to compensate for the limitations of a single optimization process [27].

In [28] the authors propose an integrated approach, consisting of both offline and online techniques. The projected framework generates throttle sequences that lead to energy saving under the constraints of trip time and computation time. This work leverages the fast-growing machine learning techniques, so to extract the optimized driving behaviours of human drivers and encode the learned knowledge into a parameter decision tree for fast online optimization. A case study on a given locomotive proved the effectiveness of the proposed framework and an energy saving of 9.84% on different running conditions can be achieved.

In [29] the authors includes a new method for speed curve definition and tracking control, based on a random reinforcement genetic algorithm (GA) to avoid the local optimum and a sliding mode controller developed for speed curve tracking with bounded disturbance.

An improved chicken swarm optimization algorithm for energy-saving for a train, by taking minimum energy-consumption, accurate stopping and punctuality as optimization objectives is in [30] without changing the existing equipment and infrastructure. Chicken swarm optimization is a global optimization algorithm, which integrates the advantages of genetic, particle swarm and bat algorithms.

In [31], the authors introduce an optimization of train speed curve applied in a real case study of the Taipei Mass Rapid Transit System for journeys from "Dingpu Station" to "Yongning Station", showing that operational energy consumption could be reduced up to approximately 58%. A real driving method to reduce the traction energy demand is presented in [32]. In this case the authors carry out theoretical optimal driving solutions thanks to a train simulation using an enhanced Brute Force searching algorithm. A driver practical training system (DPTS) is created to help drivers practice energy-efficient driving controls. A train speed trajectory optimization method associated with a driver practical training system (DPTS) is the main goal. Thanks to the DPTS, traction energy consumption is reduced by around 15%.

The authors in [33] propose a methodology that includes an objective function using cardinality and square of the Euclidean norm functions. The optimization model proposed, allows defining properly the utilization of the regenerative energy. To solve the convex relaxation counterpart of the original NP-hard problem, a two-stage alternating direction method of multipliers is designed. The procedure produces an energy-efficient timetable of trains.

Genetic algorithms have been used for a subway line in Milan and it is reported in [34]. The main goal is to fulfil the transition from a traditional system to a driverless one. It shows an energy saving increase equal to 32.89%.

2.2. Efficiency Solutions Based on Stationary and on Board Energy Storage Systems

Many studies about on board and stationary energy storage systems have been developed, especially for DC railway systems, without a reversible substation, where it is not possible to drive the surplus of regenerated energy back to the main AC power supply. Consolidated energy saving solutions using reversible substation focused on different implementations are reported in [35–41]. The innovative technologies used to design energy storage systems are super-capacitor, battery, or flywheel and IEC 62924:2017 standard fixed requirements and test methods. The International Union of Railways (UIC) with the sub commission "Energy Efficiency", creates a database where all relevant railway energy-saving technologies should be analyzed, categorized, and evaluated [42,43].

Regarding on board energy storage systems, they are already in use by some rail transit companies. The main advantages are the reduction of peak power, the stabilization of voltage, the loss reduction and the possibility to operate catenary free [44]. Real applications of on-board storage systems are the Brussels, Madrid metro and Mannheim tramway lines. The percentage of energy saving reported in [45–47] are 18.6% ÷ 35.8%, 24% and 19.4% ÷ 25.6%, respectively. To reach high integration with motor drive control, some research studies are focused on the optimal design, sizing and control of on board energy storage systems [48–52]. Focuses on stationary storage systems, the real implementation of wayside Energy Storage System (ESS), show an increase in energy savings of up to 30%. The percentage of energy saving by ESS moreover is influenced by system features and storage technologies. In [53] it is highlighted that auxiliary battery-based substations could represent a feasible solution to store the required energy for partly powering a train, supporting the electric substation during train accelerations and to compensate for voltage drops. Numerous commercially available stationary systems are available. Sitras SES (Static Energy Storage) system, marketed by Siemens, can reach up to 30% of energy saving using a super-capacitor technology that can offer 1 MW peak power for 20 ÷ 30 s, with 1400 A DC discharging current. This system is in Germany (Dresden, Cologne, Koln and Bochum), Spain (Madrid) and China (Beijing). The EnerGstor of Bombardier Company, based on supercaps, is able to reach 20% ÷ 30% of reduction of energy demand [54]. Another system super-caps based in Hong Kong and Warsaw metro systems [55] is developed, by Meiden and marketed by Envitech Energy, with scalability from 2.8 to 45 MJ of storable energy.

3. Efficiency in Electrical Vehicles Transportation Sector

The growing awareness of environmental issues, social pressures towards a solution to climate change that lead to a progressive disinvestment in fossil fuels [56] and the continuous technological improvements of storage batteries, have now led car manufacturers all over the world [57–59] to invest in new platforms for the construction of electric vehicles (EV). Electric vehicles, unlike those with an internal combustion engine (ICE), have the advantage of avoiding local emissions of greenhouse gases, or eliminating them if powered by renewable sources [60]. In fact, global emissions from electric vehicles vary according to the power generation mode. If coal plants produce the energy, they produce substantial global emissions that determine only local benefits of the use of electric vehicles [60]. Conversely, the use of alternative sources such as wind or photovoltaic allows a significant reduction in global emissions, given their lower carbon intensity [60–64]. Nevertheless, even with electricity generated from coal-fired power plants, the global emissions of an electric vehicle in the well-to-wheel cycle are lower than those ones generated by an ICE vehicle [60]. Electric vehicles are nowadays supported and encouraged by various governments around the world [65], also through measures aimed at reducing the tax burden, setting up free parking lots dedicated to them and equipped with charging infrastructures, the use of preferential lanes, access limited traffic areas, etc. [65]. An electric vehicle, unlike an ICE vehicle, allows it to be recharged from the mains, now available everywhere. However, ICE vehicles can refuel with a method dating back to the early 20th century. This refueling process started from a pharmacy that sold petrol tanks, and it was done completely manually in seconds. Electric vehicles were suffering from much longer charging times and the absence of public infrastructure, which led to their substantial disappearance to the present day [66]. In modern electric vehicles, the recharging process takes place mainly via an on-board charger; this mode requires a very long charging time, which can reach several hours [66]. Most models of electric vehicles nowadays support fast charging through dedicated infrastructures that allow, on average, to reach 80% of the state of charge (SOC) in about 30 min [67]. Nevertheless, the charging power is still not comparable to the refueling of a traditional ICE vehicle. Besides, fast charging, in addition to being more expensive, leads to faster degradation of batteries if used frequently [67].

The impact of electric vehicles on electric transmission and distribution grids is still negligible due to their low diffusion [61,68]. Their growing diffusion will inevitably cause an increase in the demand for electricity which may both have a negative impact, but also have a beneficial effect on the electricity system if well integrated [61,68]. Indeed, a further increase in the demand for electricity at peak times, because it is not restricted [68], could lead to an overload of the electric system and the underutilization of renewable sources [61,68]. It follows that leaving the decision on when to recharge without any coordination to individual users will inevitably lead to the need for further repowering of the transmission and distribution grids, premature aging of the devices and a lower quality of the energy supplied to the users [67,68].

Conversely, if recharges are coordinated among themselves with intelligent logic that also consider the actual production from renewable sources, then the electrical system it will benefit by reducing the percentage of fossil fuels in end uses [61,67,68].

To address these issues, new regulatory rules and management strategies are needed close to new technological advancements for a suitable integration of electric vehicles in the current transmission and distribution grids [69,70]. Some studies, but also common practice, have shown that on average a vehicle is parked for 95% of its life and that the weekly trips are often just the journey homework. It is from these considerations that the EVs can be seen not only as means of transport, but as active elements able to play a role in the management of power lines. The EV, once connected to the electric network, is therefore seen as an integral part of the system capable of supplying energy when demand is high (by discharging the battery) and absorbing the surplus of energy produced when demand is lower (by charging the battery) [71]. This practice is named Vehicle-to-Grid (V2G) and is based on the bidirectional power flow, from the grid to the vehicle but also from the vehicle to the grid [72,73]. When operational and integrated with the network, it can bring significant benefits such as [74]:

- Creation of electrically autonomous islands;
- Lower dependence on foreign countries;
- Better exploitation of renewable energy sources;
- Reduction of emissions for the generation of electricity;
- Increase of power quality in the network;
- Economic benefits for the user who makes their car available for the network.

All this, however, is achievable only with the introduction of the smart grid concept. This requires modernization of the transmission and distribution grids and the introduction of tools for measurement and communication. The definition of a business model, clearly defining the players involved in the value chain and fairly compensating the exploitation of EV batteries, is another crucial factor for the diffusion of such a paradigm.

On a smaller sale, V2G concept can be applied also in the context of a building (vehicle-to-building (V2B)) or of a home (vehicle-to-home (V2H)) [75]; the objective is to benefit from the exploitation of the batteries of EVs when connected to a smart system. Back up and time-shift are two examples of the possible advantages that a bidirectional interaction with EVs can bring. The higher self-consumption rate of renewable energy production achievable thanks to the exploitation of batteries, along with their lower operating costs with respect to conventional cars, represent the main driver for the integration of EVs in smart home environments.

The number of electric vehicles is expected to grow sharply in the incoming decades and the potential impact on the electric grid could be substantial. Of course, this aspect is not related to generation and transmission, in which the effect is relatively small, but it affects the distribution network in a significant way [76]. For the distribution system operator (DSO) the fluctuation of the load due to the plug in of vehicles must be minimized in order to guarantee a good quality of service for the final user. Moreover, these technical problems have to be matched with additional problematics coming from the interaction between the EV user and the grid operator, since the service must be convenient for both the grid and the owner of the vehicle.

The first mention of the vehicle to grid service was proposed by Amory Lovins in 1995, and then developed by William Kempton [76]. The main idea is that the vehicle can be considered as a storage system able to provide energy to the distribution network when parked which can be charged and discharged according to the grid necessities and price of energy fluctuation.

V2G technology can offer a wide range of functions for the grid: load balancing, harmonics suppressing, power quality improvement, peak load shaving, voltage sags reduction and interaction with Renewable Energy Sources (RES) [77]. The V2G concept is still at its first stages and is becoming more and more important as the diffusion of electric vehicles increases. From the literature [76], four key issue areas can be identified: a smart dispatching from the operator point of view, a smart charging management from the vehicle point of view, the bi-directional charger and the effect that the V2G service has on the vehicle's battery. V2G functions have a great potential for electric vehicles to become a tool for the electric grid, to manage power and energy storage applications. The challenge in developing these functions is that it is always mandatory to remember that vehicles have mobility as their primary mission and not storage system for the grid. This means that every time the vehicle's battery is used for providing services to the grid, the battery cannot be charged and discharged in a way that does not guarantee to the vehicle owner a full availability of its own car. Moreover, another critical aspect is the fact that using vehicle's batteries for providing power to and from the network contributes to the degradation of the battery, and so limitations on charge and discharge cycle must be set.

The V2G modelling has to move through the day, simulating hour by hour a real life situation, in which a certain number vehicle is generated according to a specific load profile and interacts with energy requests needed by the photovoltaic park managed by the same aggregator [78]. It is important that the fleet car has to be composed of many vehicles in order to aggregate a total power and energy storage capacity able to deal with the fluctuation of power production during the all day. The figure responsible of managing the vehicles fleet of this region is called aggregator [79].

To be more specific an aggregator is a market participant which aggregates in a unique offer the distributed generation of a certain zone. The reason for the existence of this market figure is that single distributed generation plants are usually of small size, which could be neglected in a big market like the energy one. The aggregator will be in charge of collecting both distributed generation plants and energy storage systems in a defined area. The aggregator can also be responsible for managing electric vehicles charging and discharging processes in order to guarantee to its customers a fully charged vehicle when the parking time is over while guaranteeing to its own aggregated photovoltaic plants the possibility of storing and delivering extra power when requested. The extra power, which could be managed using the fleet batteries, represents the variation in photovoltaic production, or other renewables, for the next hour with respect to the forecasted production of the day ahead.

The reason behind this definition is that the energy market is called Day-Ahead-Market (DAM), since each day the market trades the energy quantities that will be exchange during the next day. The problem is that renewable system production can be predicted but with high errors if we consider time windows of 24 h. From [79] it is possible to see that moving from 24 h ahead time windows to 1 h before the event the error on the prediction is reduced from 24% to 12%. In [80] it is shown that with an artificial neural network it is possible to predict, 24 h in advance, the irradiation during the day with an error as low as 28%. Moreover, being RES market price takers since they bid at 0 €/kWh, they will be always able to enter the market. However, the next day when the real production will change due to the unpredictability of the source there will be a lack or a surplus of energy [81,82]. This means that in the case of extra energy, part of it could be lost since the grid is already balanced thanks to the correct behaviour of the system operator, while in case of a lack of energy, additional energy is requested to traditional plants. Both these solutions act in the opposite way of a smart management of the electric grid. Moreover, when a production plant is not able to provide the energy production set during the day ahead market, it will be responsible for unbalancing the system, being subject to an unbalance forfeiture that the owner has to pay to the transmission system operator.

Some Important Considerations

As previously described, local CO_2 emissions for electric vehicles are negligible, instead they contribute to global CO_2 emissions. The latter depend on the manufacturing process of the batteries and the vehicle, but the most significant component depends heavily on the way electricity is generated. Indeed, for countries that use more renewable sources, CO_2 emissions are significantly lower than the equivalent for an ICE vehicle. On the other hand, for those countries mainly based on fossil fuels, the emissions are comparable to those produced by a very efficient ICE vehicle, as shown in Figure 1.

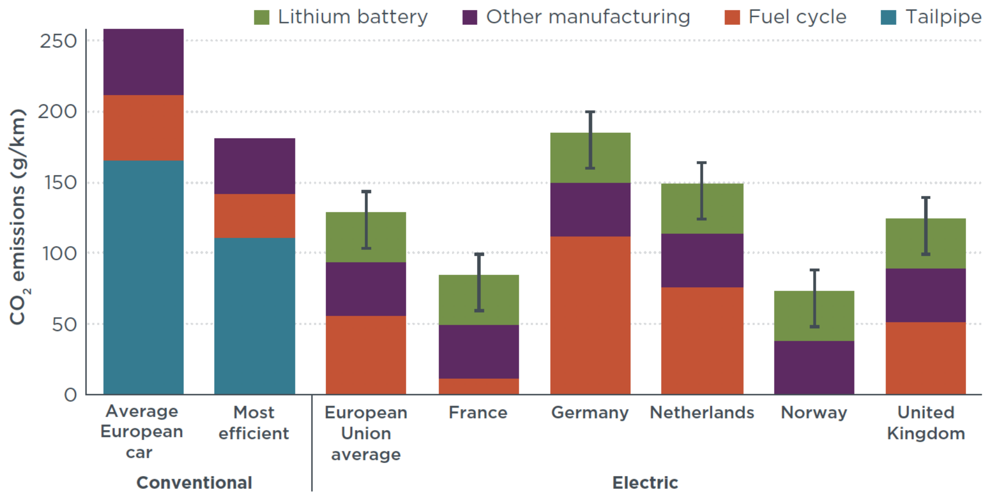

Figure 1. Life-cycle emissions (over 150,000 km) of electric and conventional vehicles in Europe in 2015 [83].

Using electric vehicles batteries for helping the grid, in managing power and energy unbalancing, could be an interesting solution since it occurs without additional costs related to dedicated storage systems.

Thanks to a full communication system between vehicles and their charging poles, it will be possible to elaborate charging strategies in order to use the parked vehicles as a supporting storage system for the grid. However, in order to have a high amount of energy available from the vehicles an aggregator will be needed.

The aggregator will be a market participant that will collect many distributed generation plants and storage systems in a certain area, in order to gather in a single figure a high amount of power increasing its impact on the market.

As a final consideration it is important to consider that if the future vehicles will be provided with batteries able to store a higher amount energy, each single vehicle will be able to exchange more energy during a discharge with a depth of 50%. This means that in that case the number of vehicles required will be even lower with respect to these simulations and the vehicle to grid function will be even more performant.

4. Efficiency in Marine Transportation Sector

International maritime shipping is the most used means to transport goods and people. In fact, global shipping is responsible of moving about 90% of the world trade, while cruise ships in 2017 allowed nearly 25 million of passenger to sail the oceans. Moreover, the availability, the low cost, and the fuel efficiency of the maritime transport made possible the growth of industrial production in emerging economies. These significant results were enabled by the ability of the shipbuilding industry to respond promptly to the market demands, despite the unfavourable economic scenario in recent years caused by the global economic crisis. In particular, at present ship designers and shipbuilders are spending a lot of effort in increasing the performance of ships, by introducing new technologies on board. Nevertheless, it is well known that shipbuilding industry is one of the hardest metal industries, characterized by high levels of raw materials and energy consumption, hazardous materials exposure, and potential risk of sea and air pollution [84]. In addition, shipping greatly contributes to the emission of air pollutants (PM, SOx, NOx), sea pollutants (noise, thermal, discharges), and greenhouse gases. In particular, the contribution of maritime transport to the latter is up to 3% of global emissions.

However, maritime transport is still the most fuel-efficient means of shipping goods, as can be seen from Figure 2. As an example, its CO_2 emissions are nearly 100 times lower than airplanes when considering the tons of goods transported over km, while presenting a similar operative range.

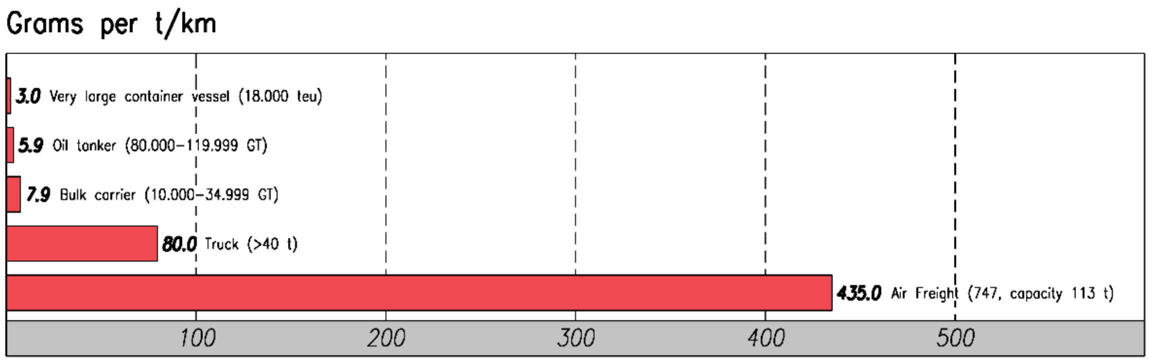

Figure 2. Comparison of typical CO_2 emissions among goods transportation options.

The shipping and shipbuilding industries are governed by global international agreements, promoted by the International Maritime Organization (IMO). In order to face the future environmental challenges caused by the expected growth of world's population and global economy, the IMO decided to set technical and operational measures to reduce ships' emissions, to be applied worldwide. In particular, in July 2011 the IMO delivered a roadmap for the reduction of environmental footprint of ships (Figure 3), by adopting the International Convention for the Prevention of Pollutions from Ships (MARPOL), Annex VI, officially entered into force in January 2013 [85].

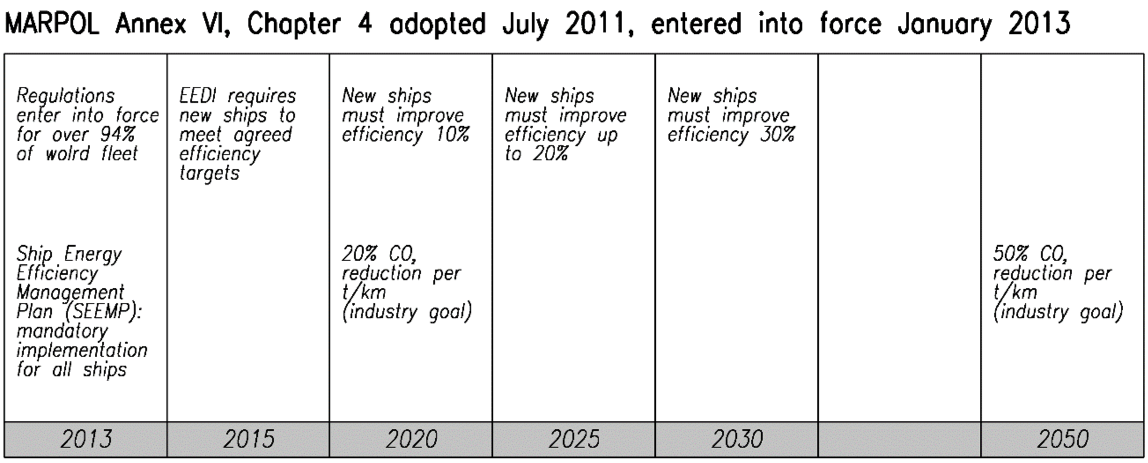

Figure 3. International Maritime Organization (IMO) roadmap for the reduction of ships' environmental footprint.

Such a decision was the result of studies about the mitigation of ship emissions started in 2005 by IMO. The resulting MARPOL annexes collect specific guidelines in this regard. In detail, MARPOL labels specific sea regions as "special areas", considering their oceanographic and ecologic importance, as well as sea traffic and risk of environment contamination. For these areas, MARPOL impose strict limits for air pollutant emissions, including volatile organic compounds (VOCs), nitrogen oxides (NOx), polychlorinated biphenyls (PCBs), sulphur oxides (SOx), chlorofluorocarbons (CFCs) and heavy metals. These substances are specifically addressed since they contribute to the creation of ozone at ground level (VOCs and NOx), rain acidification (NOx and SOx), eutrophication or oxygen depletion of inland and coastal waters (NOx), depletion of atmospheric ozone (CFCs), and the accumulation of PCBs and heavy metals in the food chain. While an emission limit is enforced all over the globe, in special areas stricter limits are imposed depending on their specific characteristics:

- SECAs, Sulphur Emission Control Areas, where there are specific requirements regarding SOx and PM emissions;
- NECAs, Nitrogen oxide Emission Control Areas where there are additional requirements regarding NOx emissions
- PSSAs (Particularly Sensitive Sea Areas), as defined in IMO Resolution A.982(24), are characterized by "unique or rare ecosystem, diversity of the ecosystem, vulnerability to degradation by natural events or human activities, significance of the area for recreation or tourism, biological research value, or historical value".

4.1. Increasing the Efficiency of Ships

The most obvious way of limiting the environmental footprint is the reduction in fuel consumption, which means increasing the overall efficiency of ships. Thus, the shipbuilding industry is continuously working towards improving hull forms, engines, and propellers. Setting aside the hydrodynamic area, the reduction of the ship's pollutant emissions down to a level compliant with the above-depicted goals can be reached by means of three strategies [86]. These are: the switch to a different, cleaner, fuel (e.g., low sulphur fuel oil, natural gas, methanol, etc.); the installation on board of equipment for exhaust gas treatment (e.g., SCR, scrubbers, etc.); and the improvement of a ship's electrification. The use of other fuels can lead to different results, both on the pollutant emissions reduction and the overall ship's fuel consumption, depending on the specific fuel used. The second method is an application of technical solutions already used in other fields, like automotive and land power generation, with some specific modifications due to the particular marine environment. These two strategies have pros and cons, but are both aimed at improving the internal combustion engines (ICEs) performance in terms of pollutant emissions. Conversely, the electrification option implies substituting existing ICE with electrical motors, thus providing: an increase in power output controllability and power density; a reduction in noise, vibrations, heat, and maintenance complexity; more degrees of freedom for arranging the engines in the engine room. Thus, similarly to what is happening in other transportation modes, electrification is one of the most applied methods to improve ships' efficiency and reduce their environmental footprint [87]. Obviously, given the power required by a ship (as an example, the propulsion system of a cruise liner can reach a power of tens of MW [88]), the primary source of electric power is commonly a set of ICE powered generators. In particular, diesel generators are the most used, but generators powered by gas turbines can be also found, typically in naval applications. For these generators, the use of different fuels and the adoption of exhaust gas treatment are viable options to reduce further the ship environmental impact. Other methods to generate electric power are starting to be applied, like fuel cells. Regarding the latter, their use as main power sources is limited to small crafts, while there are some experimental installations on board large ships of fuel cells as auxiliary generators.

However, at present there is no viable option for totally powering a big ship without using fossil fuels. Indeed, the significant energy density of fossil fuels is one of the enabling factors that make big ships feasible, given their scope of work and their typical routes. To give an example, the very large container and bulk carriers that are used to ship goods all around the world require a range of up to 7500 nautical miles to be usable (e.g., the route from the port of Singapore to the port of Trieste is circa 7100 nm long, and must be sailed without intermediate stops to avoid lengthening transport times, and thus losing money). This means that such ships have up to 5000 m^3 of fuel on board, which is usually replenished only at the departure and arrival ports. Conversely, ships for local transport (in a range of a thousand nautical miles) have nearly 1000 m^3 of fuel on board, and the refuelling is done only at the home port due to economic reasons (there are bilateral contracts and national taxation differences among ports, making the refuel in other ports not economically convenient). Besides the energy density of fossil fuels, which is still not in the reach of present energy storage systems and other energy production systems, there is also the issue of the refuelling times. In fact, a ship's refuelling is usually done by means of tanker ships, that have tanks and pumps installed on board, dedicated to such a task. The tankers can refuel a large ship at nearly 500 m^3/h, while smaller ships (the local transport ones) are usually refuelled up to 250 m^3/h, by using in both cases electric pumps that can reach 2–3 MW of power. These figures mean that a complete refuel can be achieved in 10 h for a large ship, and 4 h for a small one (excluding all the logistic and preparation times). By assuming a volumetric energy density of about 36 MJ/l for the fuel (that is nearly 10 MWh/m^3), it is possible to calculate an equivalent refuelling power of 5 GW for a large ship, and 2.5 GW for a small one. Even assuming that it is possible to install on board an energy storage system capacity capable of delivering the required autonomy, the required recharging power level is so high it may be unsustainable for actual port power systems. For the tankers, these are refuelled in their port, with a speed that is very dependent on the specific port operation. Thus, at present, the focus on ships is given to the increase of the overall fuel efficiency of the ship, focusing on the different aspects stated above.

Considering only the propulsion system electrification, several different architectures can be applied. The first is the series configuration, where the propellers are powered by electric motors, and ICEs are used only to generate electric power (Figure 4). The second configuration is the parallel one, also called hybrid propulsion system [89], where electric motors and ICEs are both connected to the propeller (Figure 5).

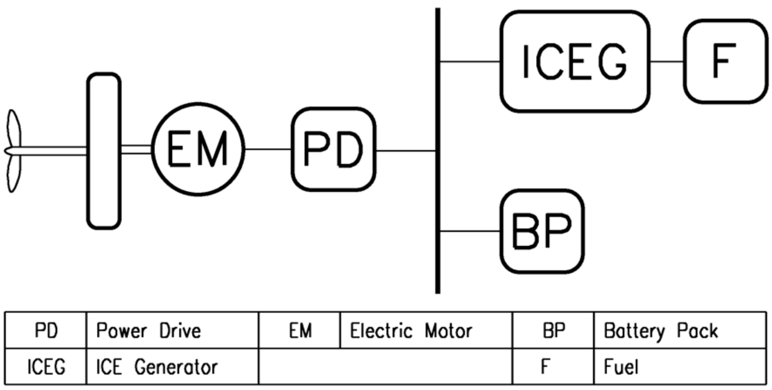

Figure 4. Electric propulsion, series configuration.

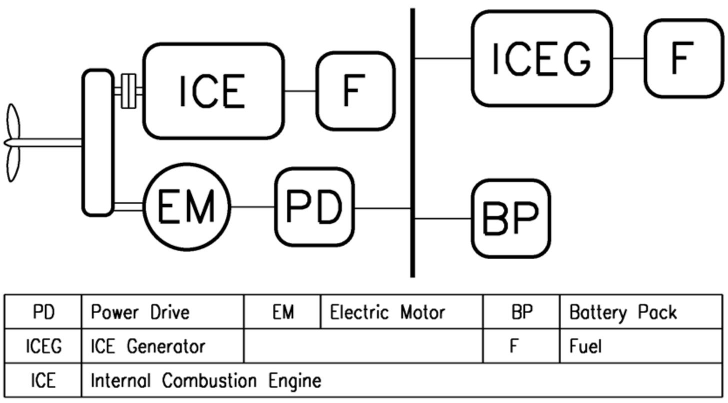

Figure 5. Electric propulsion, parallel configuration.

For ships with ship services loads requiring a significant electric power (e.g., cruise liners), the integrated power system (IPS) configuration is a viable option (Figure 6) [88]. In such a case, the same set of ICE generators is used to power both the propulsion and the other loads through a single power system [90]. Such a configuration allows obtaining a reduction in the total size of on-board generators in respect to the use of separated sets of generators, one for each subsystem. Moreover, the IPS architecture can exploit either the series or the parallel configuration for the propulsion system, depending on the ship operative requirements. Nowadays, the evolution in power electronics is pushing forward the performance levels achievable from the electric drives, leading to the pervasive presence of power electronics converters on board ships. These can be used to control electric motors, manage power flows on the power system, and interface energy storage systems, leading to the so called integrated power and energy system (IPES), shown in Figure 7 [91,92].

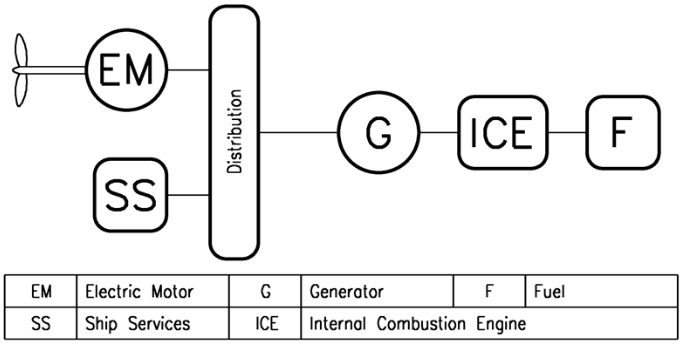

Figure 6. Integrated power system architecture.

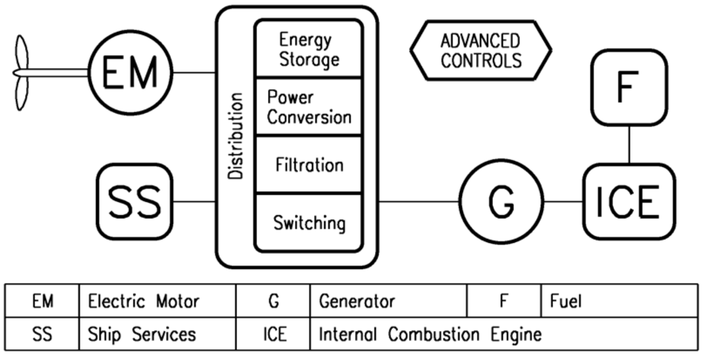

Figure 7. Integrated power and energy System architecture.

The integration of energy storage systems is useful for further increasing the overall ship efficiency. In fact, small ships can sail short routes on stored power only, while big ships can use energy storage systems as a transitional source of power to be used in emergency, avoiding running additional generators in some operative conditions. Moreover, storage systems can be used to perform peak shaving, allowing installing on board smaller generators, with a consequent reduction of weights, volumes, and overall fuel consumption [93].

In addition to the propulsion system electrification, also the replacement of mechanically driven equipment (e.g., pumps, cranes, etc.) with electrically driven ones is a viable option to increase the overall ship efficiency. The coupling of these new electric loads with power electronic converters enables further improvement in efficiency, reliability, and performance, by removing mechanical regulation equipment. Obviously, the introduction of these additional loads requires an increase in the on-board generators' power, further motivating the shift towards IPS or IPES configurations for ships.

4.2. The Issue of Designing Efficient Ships

The design of a ship is a complex process, because it is necessary to integrate different subsystems in a reduced space with several constraints. In fact, each subsystem is needed for the correct operation of the ship, but at the same time, it is in competition with the others for space and weight allocation. Ship designers have to consider both naval architecture issues (e.g., stability, hull form, manoeuvrability, structure, etc.), ship's operative requirements, costs, efficiency, and so on. The ship designers must in fact design a system of systems [94], where the optimal design solution for the overall ship is never the sum of the optimal solutions for each subsystem design. In fact, in the shipbuilding industry the most significant proof of concept is not related to the demonstration of a working technology. Instead, it is given by the demonstration of achievable results in improving ships' key performance indicators (KPI—such as space, weight, safety, and efficiency). Thus, a promising technology which is able to increase the efficiency of a single subsystem may prove to be irrelevant for increasing efficiency in a ship, or may worsen it either due to its effect on other subsystems or due to the ship's specific operative requirements. As an example, electric propulsion allows a significant reduction in fuel consumption compared to mechanical propulsion mechanisms in ships with several different operative speeds, thanks to the small loss of efficiency of electric drives at variable loads. Conversely, ships sailing for long times at constant speed (e.g., tankers) achieve the lowest fuel consumption by using mechanical propulsion, due to the high efficiency of low speed 2-stroke diesel engines when operated at their optimal load point.

In such a context, integrating new technologies dedicated to the efficiency increase into an existing ship is an engineering challenge, possibly being unfeasible or requiring an amount of modifications so high as to make the obtainable gains not justifiable. Likewise, the design of a new ship able to exploit new subsystems to achieve a more efficient operation is a complex task too. Ship designers have to take into account the integration of the new technologies since the first stages of the ship design (i.e., the early stage design), to assure their correct on board exploitation [95–97]. Such an approach is required, since the most impacting decisions about ship design are taken during the first stages of the design process, and cannot be changed on later stages without deeply affecting costs and times. For common ships' designs, the previous knowledge base is, in general, sufficient for making a correct guess about viable design solutions. Conversely, technologies with a significant impact on the ship's KPI may require proceeding with several tests before reaching a feasible design [98].

To overcome the need of making design choices based on uncertain data, tools are being created. In fact, the advancements in information technology led to the creation of software tools, aimed at easing the designers' work [92,99,100]. These tools allow inferring the effect of the design choices overall ship, already during the early stage design. Consequently, designers can compare different solutions in terms of the ship's KPI, possibly leading to the choice of the best overall design. Moreover, such tools provide a means to assure the correct on board integration of innovative technologies, thus ensuring the achievement of the expected efficiency increase, as well as other advantages [101].

Finally, it has to be highlighted that the pursuit of an increase in ships' efficiency may have a significant impact also on other applications. The most obvious case is the need to connect the ship to the port electrical power system (i.e., shore connection [102,103]), for recharging on-board installed energy storage systems or at least shutting off on-board generators. Such a practice can reduce the pollutant emissions in the ports (which are commonly placed inside cities), as well as increase the overall system efficiency (ship's on board generators have a higher CO_2 footprint in respect to the land power grid). However, in order to use a shore connection a specific set of equipment is to be installed on the berth, and the port power system may need to be refitted to support the additional load (e.g., a cruise ship requires up to a MW when at berth). Another example of the global impact of efficiency increase methods can be made referring to the use of cleaner fuels. Indeed, besides the modifications to ship's engines and fuel treatment systems, it is required to create a dedicated supply chain for these new fuels.

5. Conclusions

The paper includes a comprehensive review on efficiency issues related to three important sectors of the transportation systems: railways, electrical vehicles and marine. The measures recently investigated and implemented, for improving three transportation systems from the point of view of efficiency, are reported and analyzed. Many actions deal with the application of devices, apparatus and systems that can improve the efficiency acting on the infrastructure, but other several actions deal with the suitable management techniques for existing systems, also with the aim of integrating them in a wider system. The analysis pointed out that a common way to compare the increased efficiency of the transportation system in the three analyzed sectors is to assess the percentage reduction of the

CO_2 emissions, thanks to the implementation of different electrification solutions of various means. For the rail transport sector, these solutions are related to changes to an already existing electrical infrastructure, that can be integrated with innovative devices (e.g., storage) and management systems (e.g., traffic control), differently from the on road and maritime sectors, where the improvement of the efficiency can be achieved through electrification actions of the vehicles and of the propulsion systems.

However, there are several different factors that make a direct comparison among the different transportation systems a very complex work. First of all, railway, road, and marine sectors can be either integrated or mutually exclusive transportation means. Indeed, for goods transportation at present there is a good integration among them, which implies using ships for long-range transportation, then railways for medium range transportation, and finally road vehicles for short range delivery. This means that a complete assessment of the efficiency of the goods transportation framework includes all of the above described systems, with ratios that depend on the specific start and finish point. Conversely, the people transportation is caused by a different set of needs and aims, depending on the transportation system. Road and railway transportation can be partially overlapped in this regard (excluding locations that are not reachable by train only), while ships are used either for marine routes that cannot be achieved by other means, or for leisure trips. This makes an efficiency comparison among the three systems fully dependent on the specific type of application and route. A second critical point in such a comparison is the strict dependency among the CO_2 footprint of the recharging energy, for grid connected vehicles. As depicted in this paper, different countries have different energy mixes for producing the electrical energy, making it possible to compare these figures for short range transportation only. As an example, the CO_2 emissions of an electric truck that delivers a given set of goods going through different countries is a composition of the amounts of emissions given by the energy mixes used in the places where it stops for recharging. Moreover, given a single starting point and a single arrival point, different routes can be taken, implying different energy consumption and different recharging energy mixes. Thus, a single figure, able to provide a full assessment and comparison of the efficiency among the presented transportation systems cannot be provided.

So, independently from the common metric for the assessment of efficiency and its improvement (in relation to different solutions adopted in the three transport sectors), the main result of the review reported in this paper has been collecting all the possible measures that can be applied to the three transport sectors for improving the efficiency, in function, of their peculiarities. It contributes to the idea of what has been already done within this field and what could be the margin of development to be explored in the future.

Author Contributions: Conceptualization, M.B., M.C.F. and G.S.; methodology, M.B., M.C.F. and G.S.; validation, M.B., M.C.F. and G.S.; investigation, V.B., F.F., A.R., A.V.; resources, V.B., F.F., A.R., A.V.; data curation, V.B., F.F., A.R., A.V.; writing—original draft preparation, V.B., F.F., A.R., A.V.; writing—review and editing, M.B., M.C.F. and G.S.; supervision, M.B., M.C.F. and G.S., M.C.F. and A.R. mainly contributed on Section 2; M.B. and F.F. mainly contributed on Section 3; V.B., G.S., and A.V. mainly contributed on Section 4. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare that there is no conflict of interest regarding the publication of this paper.

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