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ABSTRACT

A brownfield container terminal aims to realize a zero-emission vehicle fleet by 2040. To prepare for the fleet investments, the terminal wants to ascertain the consequences for its costs and operational performance of implementing a new generation of zero-emission equipment for the horizontal transportation of the containers at the terminal. To address this issue, a literature research is carried out to formulate the technological criteria for energy carriers and to identify possible energy sources that could facilitate the transition from a fossil fuel-based vehicle fleet toward a zero-emission vehicle fleet. The list of possible energy carriers is reduced by an assessment. The outcome of the assessment results in two best options, namely, the lithium-ion battery and hydrogen, for the vehicle fleet. Consequently, a discrete event simulation is carried out to assess the operational performances of these two energy carriers. This approach can be applied for many other terminals that are exploring ways to achieve a zero-emission fleet.

Keywords: container terminal, horizontal equipment, lithium-ion battery, hydrogen, discrete event simulation

INTRODUCTION

The combustion of fossil fuels generates greenhouse gases (GHGs). Since the beginning of the Industrial Revolution (around 1750), human activities have increased the concentration of carbon dioxide in Earth's atmosphere by almost 50%. The GHG effect is currently one of the world's biggest challenges (*1*). Carbon dioxide enters the atmosphere when fossil fuels (coal, natural gas, and oil) are burnt. To stop this process and prevent the world from disaster scenarios, the Paris Climate Agreement was reached (*2*). According to the Paris Agreement, fossil-fuel use must decline, emissions should be reduced to at least 40% (compared to 1990) by 2030, and a climate-neutral world should be achieved by 2050. This puts increasing pressure on governments and companies, and it particularly plays an important role in the transport sector, given that the transport sector accounts for one-third of GHG emissions in the European Union; this figure rises to almost a quarter globally (*3*-*4*). To illustrate, approximately 40% of all Dutch CO_2 emissions come from the five Dutch seaports. The brownfield container terminal studied here is a stevedoring company. The terminal has reduced a significant percentage of its CO_2 on-site emissions compared to its 1990 levels. However, it has set an even more ambitious target of being emission free by 2040. An energy- and environmentally friendly fleet has been mentioned as one of the most important initiatives to be taken by container terminals (*5*). New developments such as hydrogen, electrification, hybrid technology, and energy regeneration have significant potential to reduce or even eliminate on-site emissions caused by container handling equipment (*6*). The transition toward a zero-emission container terminal should be taken in an economically responsible way. During the transition, a balance is required between the pace of transition and the investment program. To shift from the current vehicle fleet using fossil fuels toward a zero-emission vehicle fleet is a first step in a replacement and investment agenda. This research aims to research which of the possible renewable energy sources are feasible to realize a zero-emission vehicle fleet. The central research objective in this paper is to identify the consequences for costs and operational performance of implementing renewable energy sources.

To address this issue, the remainder of this article proceeds as follows. A brief literature review provides state-of-the-art knowledge on possible energy carriers. The methodology applied is described in the next section, combined with the results of semi-structured interviews and screening. Further, a description of the discrete simulation model is given and the outcomes are discussed. This paper ends with a conclusion and discussion.

LITERATURE STUDY ON ENERGY CARRIERS

The transport sector is currently characterized by a strong dependence on fossil fuels. The International Maritime Organization's GHG strategy has sent a clear signal that now is the time to start developing the vessels, the fuels, and all the other necessary infrastructure to support zero-emissions from shipping (*7*). One obvious development direction is therefore the use of alternative energy sources or alternative energy carriers. The latter category includes the massive electrification of the transport sector and related logistics functions. Energy resources can be roughly classified into three categories: renewable, fossil, and nuclear. Alternative energy carriers can only be considered as renewable when the production takes place through wind, water, or solar power. In this research, energy carriers are considered only when they can be implemented in the current energy system. The next section explains a few possible energy carriers of this type.

Lithium-ion batteries

Lithium-ion batteries are favored in modern transportation, where they have become the dominant battery type for some transport applications, and their application in future electric vehicles is undeniable (*6*, *8*-*9*). A major risk of lithium-ion batteries is uncertainty about meeting the growing demand for lithium on time (*10*). It is predicted that this growing demand will outstrip the supply of rare earth elements (*11*). Notwithstanding this major risk, lithium-ion batteries have become the most widespread form of zero-emission road vehicle technology for several reasons. They do not contain any particularly toxic materials, but they do contain metals such as nickel or cobalt (*11*). Moreover, lithium-ion batteries can respond within milliseconds and have high round-trip efficiencies (*12*). Additionally, lithium-ion batteries: are relatively efficient, have low per-mile costs, have low maintenance costs, and create no emissions from the vehicle (*6*). The big advantage of lithium-ion batteries is that they lack the memory effect, ensuring that they do not have to be discharged first to recharge them. However, lithium-ion batteries are limited in range and in the amount of energy that they can store (*6*,*12*).

Lead-acid batteries

Lead-acid batteries are another type of battery found in electric vehicles. Lead-acid batteries, invented in 1860 by French physicist Gaston Planté, were the first rechargeable batteries and are still the most widely used type of rechargeable batteries (*13*). Their negative plate is made from lead metal and their positive plate is made from brown lead dioxide. The electrical energy stored in the battery can be converted from chemical energy into electrical energy (*14*). According to Schmidt et al. (*15*), lead-acid batteries are further standardized for heavy-duty vehicles. Some container terminals use lead-acid batteries.

Hydrogen

One scenario often mentioned is the short-term use of hydrogen to generate electricity in heavy transport or at container terminals and in warehouses. A future energy system without hydrogen as an energy carrier is impossible according to many researchers (*16*-*18*). Hydrogen is a chemical element that can be stored in a hydrogen tank to be converted to a fuel cell on the vehicle to produce electricity (*19*). Hydrogen itself is not a source of energy, but it can be used as an energy carrier that has no pollutant emissions at the time of use (*3*, *6*, *12*). There are three types of hydrogen: grey, blue, and green. Grey hydrogen is hydrogen generated from fossil fuels, most commonly coal and natural gas (*11, 20*). Blue hydrogen is also created by fossil fuels, but the GHG emissions produced as a residual product are stored underground in carbon capture storage. This type of hydrogen can be used as an aid in an energy transition phase toward fully renewable energy carriers (*11, 20*). Green hydrogen is hydrogen produced using sustainable energy, for example by wind or solar power converted into hydrogen employing electrolysis (*11, 20*). Hydrogen produced from green electricity emits no CO_2 or other GHGs.

Ammonia

Ammonia, an inorganic compound of nitrogen and hydrogen with the molecular formula NH_3, is the most produced industrial chemical worldwide (*21*). Its structure is not flat; rather, it forms a tetrahedron with the nitrogen in the center. Ammonia is neither as stable as H_2O nor as unstable as H_2. It has a high hydrogen content of 17.7% and an energy density of 3 kWh/kg (*22*). Ammonia can be produced from N_2, and fossil, nuclear, or renewable H_2, or directly from N_2 and H_2O via electrochemical, photochemical, or chemical looping processes. Ammonia exists mostly in gaseous form. According to Xue et al. (*21*), there is increasing interest in using renewable ammonia as an energy carrier given the continuous depletion of fossil fuels and concerns about climate. Other research states that ammonia should be used as an energy carrier to improve the overall security of the energy supply, by making the system resilient to energy supply disruption through a convenient and inexpensive means of energy storage (*23*). Ammonia is increasingly attractive as an energy carrier because of its high energy density and its potential of being a zero-carbon fuel. Applications of ammonia in heavy transport, power generation, and distributed energy storage are being actively developed. Produced at scale, ammonia could replace a substantial fraction of current-day liquid fuel consumption (*24*). However, there are many safety concerns about ammonia (*25*).

METHODOLOGY

Semi-structured interviews with suppliers of vehicles (carrying the containers) are carried out to obtain information on their long-term vision for energy carriers. A screening process is applied to select the most feasible alternatives from the literature study. The screening strategy applied in this research is *bounded space of promising alternatives* (*26*). The alternatives are selected by placing constraints on the characteristics that alternatives must possess, and selection takes place before the detailed evaluation of the alternatives. If the alternative does not have certain characteristics, it is eliminated from the list of promising alternatives. The constraints on characteristics are chosen by applying an objectives tree.

The alternatives selected are used for the next phase of the research, which entails discrete event simulation. Discrete event simulation is used to assess the possible energy carriers for use at the terminal. The model is developed in SIMIO (*27*). To sustain the model's correctness, Sargent's modeling cycle (*28*) is followed.

Results of evaluating the energy carriers

All suppliers interviewed are currently using lithium-ion batteries for their vehicles, and some are using lead-acid batteries. Also, one of them is using hydrogen range extenders for its vehicles. The future vision of all suppliers is quite comparable. They all believe in lithium-ion batteries, or hydrogen, or both. This future vision is especially important for this research as one of the objectives is a good long-term vision about energy carriers, which needs to be realized to achieve the main goal of running a good zero-emission vehicle fleet. The characteristics on which the alternatives are screened are 'long-term vision', 'mass volume product', and 'matureness'. Only the alternatives that possess all three characteristics – lithium-ion batteries and hydrogen energy carriers – are selected in the screening. Both alternatives are applied in the simulation model.

Simulation model setup

Figure 1 shows the black-box representation of the terminal. The system's input is twofold: containers and properties of the vehicles. Containers are input for the simulation model as they arrive at the quay crane (QC) or stack and start the simulation model. Two types of containers enter the system: 20ft and 40ft containers. Next, the properties of the vehicles are input for the system. The vehicles have multiple important properties such as their speed, the distances they drive, and fuel consumption. These are all fixed variables and, therefore, input for the system. Variables that are fixed in only one simulation run are the control parameters. The control parameters for this simulation model are the number of vehicles, the refueling or charging time, and the number of spots available at the fuel station. The output of the simulation model is also twofold: physical output and information. The physical output of the simulation model is the containers; all other output is information, which is imported to be able to provide conclusions on the simulation model.

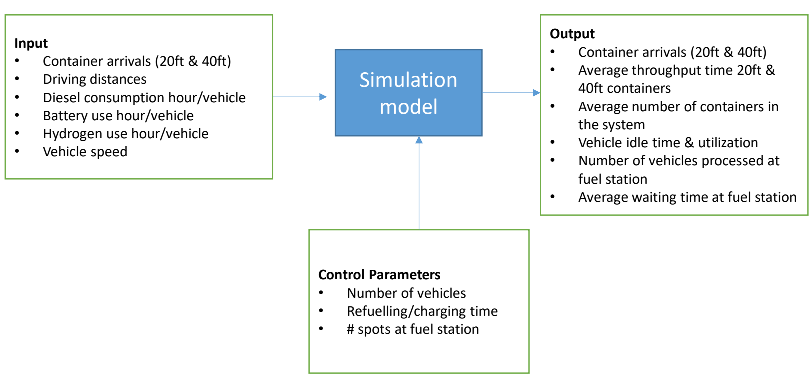

Figure 1. Specification of input, control parameters, and output of the simulation model.

The process simulated as in Figure 2 starts with QCs loading containers on the vehicles 1 and 2 The QC is simulated as a black box, as this vehicle is outside the scope of this research. According to an arrival rate, containers arrive from the QCs. Then, QCs deliver the containers to vehicles, which deliver the containers to the Automated Stacking Crane (ASC) 3 and 4.

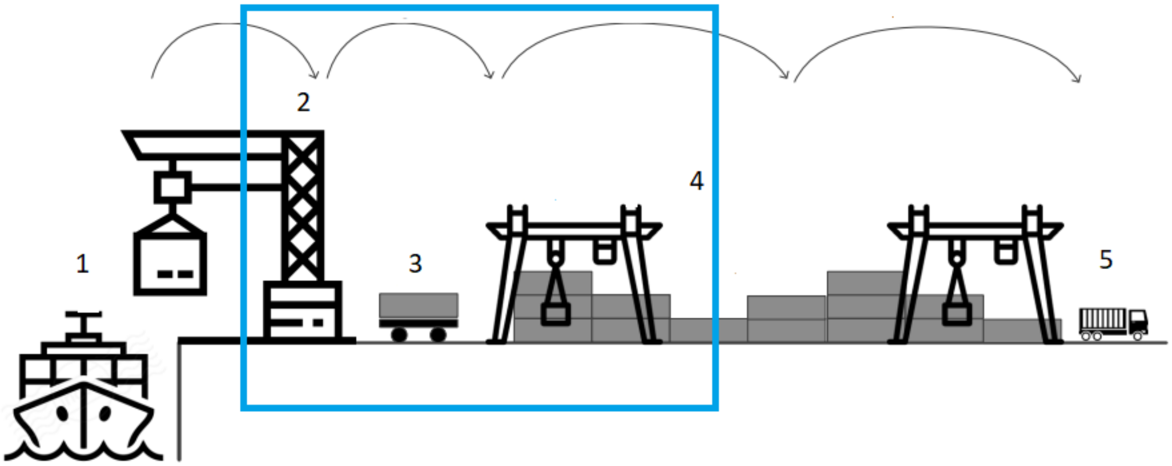

Figure 2. Demarcation of the simulation (enclosed in blue box).

Simplifications are incorporated in the model to enable more rapid model development and use, and to improve transparency (*29*). The following assumptions are made:

- Business continuity has the highest priority; therefore, it is of great importance that the container does not have to wait for a vehicle to transport it to the QC or ASC.
- The terminal operates 24/7.
- The container arrivals are split in two: the arrival of 20ft containers and the arrival of 40ft containers. To reduce the number of entities in the model, only containers following the most common route arriving via the quay and leaving the terminal via an external truck are modeled. This represents 19.19% + 12.38% = 31.57% of all the containers. The rest of the containers enter and leave the terminal differently.
- The tank content of the vehicles is 1400 liters and all vehicles start with a full tank (**Table 1**).
- Vehicle refueling takes 15 minutes. In reality, the vehicles report a low fuel level at 100 and 200 liters of diesel, but the refueling threshold in the simulation is 200 liters of diesel. As soon as the vehicle reaches the control point and it has less than 200 liters, the vehicle is sent to the refueling station.
- There are exactly enough vehicles available to handle the current amount of container throughput (**Table 1**). For one month, the 20ft container throughput is 80,244 and the 40ft container throughput is 157,273. The distances are not shown for reasons of confidentiality. All distances (QC to ASC, ASC to QC, and to diesel stations) and average speeds are used to calculate the energy consumption for each type of vehicle.

Table 1. Types of vehicles and their specifications

Vehicle type	Total #Vehicles in SIMIO (31%)	Fuel/driving hours (Liters)	Diesel tank capacity (Liters)
CT60H	9	26.00	1,400
CT60P	25	24.00	1,400
CT60N	4	14.00	1,400
VDL	27	7.20	2x700

Experimental setup

Table 2 provides the experimental plan for this research. Experiment 0 is the current situation at the terminal. It consists of 65 diesel vehicles, vehicle refueling takes 15 minutes, and two vehicles can be refueled at the same time. Experiments 1 to 12 represent the first scenario using the battery-electric vehicles instead of diesel vehicles. The number of vehicles, charging time for the lithium-ion batteries, and the number of chargers is changed in the experiments to test for the best combination. Currently, the number of vehicles needed to handle the container throughput is 65. From an interview with a supplier, it is known that more battery-electric vehicles are needed because they need to be charged more often. Therefore, the experiments for battery-electric vehicles contain 70, 75, and 80 vehicles.

Experiments 13 to 20 represent the second scenario: the terminal with hydrogen vehicles. The experiments with hydrogen vehicles contain 65, 70, 75, and 80 vehicles. To be able to compare the battery and hydrogen scenarios to the base case, the container throughput is kept equal. Container throughput is one measure of the efficiency of port operations. It is assumed that the efficiency of port operations at least remains the same in the future. Based on the simulation outcomes, two additional experiments (21 and 22) are added for each scenario.

Table 2. Simulation experiments

Experiment	#Vehicles (Diesel)	#Vehicles (Battery)	#Vehicles (Hydrogen)	Fuel/charging time (Min)	# Spots at fuel/charging station
0	65	0	0	15	2
1	0	70	0	30	10
2	0	70	0	30	20
3	0	70	0	60	10
4	0	70	0	60	20
5	0	75	0	30	10
6	0	75	0	30	20
7	0	75	0	60	10
8	0	75	0	60	20
9	0	80	0	30	10
10	0	80	0	30	20
11	0	80	0	60	10
12	0	80	0	60	20
13	0	68	0	13	10
14	0	0	65	14	2
15	0	0	65	14	4
16	0	0	70	14	2
17	0	0	70	14	4
18	0	0	75	14	2
19	0	0	75	14	4
20	0	0	80	14	2
21	0	0	80	14	4
22	0	0	70	14	1

RESULTS OF SIMULATION STUDY

The results of the experiments are discussed in this section and tabulated in **Table 3**.

Reference case – diesel vehicles (Experiment 0)

The reference case in the simulation model is a representation of the current situation at the selected terminal. The model is a validated model, as the results of Experiment 0 are exactly as expected. The average flowtime of 20ft containers is 2.21 hours and of 40ft containers is 0.09 hour. This difference in flowtimes can be explained by the following two reasons. The vehicles transport one 40ft container at a time and two 20ft containers. Thus, an arriving 20ft container always has to wait for another 20ft container before being transported, and this increases the flowtime of the first 20ft container. A second explanation for the difference in average flowtime is a lower number of incoming 20ft containers than 40ft containers. During the simulation period, 80,246 20ft containers arrive at the terminal and 157,276 40ft containers arrive – thus almost twice as many 40ft containers. Proportionally, the fact that a 20ft container has to wait longer for the next one explains the longer flowtime for 20ft containers. In Experiment 0, 280 vehicles are allocated to the fuel station – meaning that every vehicle needs to refuel approximately four times during the simulation period. This is validated by an employee of the terminal. The time that the vehicle has to wait before refueling is so short that it is negligible. Moreover, the fuel station is utilized just 4.79% of the time, indicating that there is enough capacity at the fuel station.

Table 3. Results of the simulation experiments

	# Vehicles	Fuel/ charging time (min)	# Spots at fuel station	Tank / battery capacity	Avg. idle time (%)	Std dev. idle time	Avg. utili- zation (%)	Std dev. Utili- zation	Avg. flowtime 20ft container (hours)	Avg. #20ft container in system	Avg. flowtime 40ft container (hours)	Avg. #40ft container in system	# Vehicles handled at fuel station	Avg. waiting time at fuel station (hours)
0	65	15	2	1400L	64.51	18.87	35.49	18.87	2.0484	225.17	0.0860	18.53	237	0.0000211
1	70	30	10	412kWh	66.46	19.90	33.54	19.76	2.3798	261.60	0.0876	18.87	1317	0.0000365
2	70	30	20	412kWh	66.46	19.90	33.54	19.76	2.3798	261.60	0.0876	18.87	1317	0.0000235
3	70	60	10	412kWh	65.82	19.39	34.18	19.25	3.0999	340.72	0.0891	19.20	1320	0.0000479
4	70	60	20	412kWh	65.82	19.39	34.18	19.25	3.0999	340.72	0.0891	19.20	1320	0.0000365
5	75	30	10	412kWh	68.72	20.93	31.28	20.79	2.5971	285.49	0.0875	18.85	1316	0.0000365
6	75	30	20	412kWh	68.72	20.93	31.28	20.79	2.5971	285.49	0.0875	18.85	1316	0.0000235
7	75	60	10	412kWh	68.09	20.59	31.91	20.45	2.6504	291.34	0.0893	19.24	1317	0.0000479
8	75	60	20	412kWh	68.09	20.59	31.91	20.45	2.6504	291.34	0.0893	19.24	1317	0.0000365
9	80	30	10	412kWh	70.65	21.65	29.35	21.51	2.6975	296.53	0.0875	18.86	1315	0.0000365
10	80	30	20	412kWh	70.65	21.65	29.35	21.51	2.6975	296.53	0.0875	18.86	1315	0.0000235
11	80	60	10	412kWh	70.11	21.37	29.89	21.24	2.6888	295.58	0.0891	19.20	1316	0.0000479
12	80	60	20	412kWh	70.11	21.37	29.89	21.24	2.6888	295.58	0.0891	19.20	1316	0.0000365
13	68	30	10	412kWh	64.80	19.20	35.20	19.20	2.0354	223.74	0.0859	18.57	1317	0.0000365
14	65	14	2	30kg	64.63	19.08	35.37	18.93	2.5207	277.02	0.0858	18.48	61	0
15	65	14	4	30kg	64.63	19.08	35.37	18.93	2.5207	277.02	0.0858	18.48	61	0
16	70	14	2	30kg	67.23	20.36	32.77	20.22	1.9664	216.16	0.0855	18.43	61	0
17	70	14	4	30kg	67.23	20.36	32.77	20.22	1.9664	216.16	0.0855	18.43	61	0
18	75	14	2	30kg	69.41	21.22	30.59	21.17	2.1464	235.95	0.0856	18.43	61	0
19	75	14	4	30kg	69.41	21.22	30.59	21.17	2.1464	235.95	0.0856	18.43	61	0
20	80	14	2	30kg	71.33	21.93	28.67	21.79	2.1695	238.48	0.0855	18.43	61	0
21	80	14	4	30kg	71.33	21.93	28.67	21.79	2.1695	238.48	0.0855	18.43	61	0
22	70	14	1	30kg	67.23	20.36	32.77	20.36	1.9664	216.16	0.0855	18.43	61	0

Scenario 1 – Usage of lithium-ion batteries (Experiments 1 to 13)

The first scenario is the scenario where lithium-ion batteries are used for the vehicles. The lithium-ion batteries contain 412 kWh of energy. The electric vehicle battery consumption is directly related to the distance traveled and consumes 13.2 kWh per hour. When the battery level reaches 20% of the remaining power (82.4 kWh), the vehicle finishes unloading its current entity and travels to the charging station. The threshold of 20% is assumed because multiple studies show that deep battery discharges could significantly decrease the lifetime of the battery. The battery is charged up to 80%, for the same reason; therefore, the battery will be charged until it contains 329.6 kWh. Dedicated quick charging is used to charge the lithium-ion batteries because this is the easiest implementation method at a brownfield container terminal compared to charging or battery swapping. According to one battery supplier, the charging time of a lithium-ion battery is less than 1.5 hours; therefore, charging the vehicle takes either 30 minutes or 60 minutes, depending on the experiment. The charging efficiency is over 85%.

For Scenario 1, Experiment 13 gives the best results: 68 vehicles with a charging time of 30 minutes and 10 spots available at the fuel station are required to maintain the same container throughput. As the simulation model incorporates 31.57% of all containers, the total number of vehicles required is 215 battery vehicles with a charging time of 30 minutes, and 32 available spots are required at the fuel station to maintain the same container throughput.

Scenario 2 – Hydrogen vehicles (Experiments 14 to 20 and Experiment 22)

The second scenario is the alternative of using hydrogen as an energy carrier for the vehicles. As no hydrogen vehicles (suitable for terminal operations) are available on the market yet, a lot of assumptions are made. As soon as more knowledge is available about hydrogen vehicles, these numbers can be changed as parameters in the model. To assign realistic parameter numbers to the hydrogen vehicles, examples relating to the Hyundai hydrogen truck and hydrogen buses are applied (*30*). It is assumed that the hydrogen fuel cells in these vehicles store compressed hydrogen (gaseous form). To store hydrogen as compressed gas, the hydrogen pressure must be 350-bar or 700-bar (*31*). Hydrogen stored at a higher pressure has a higher energy density than hydrogen stored at a lower pressure. Therefore, currently, cars with a hydrogen storage tank are commonly equipped with 700-bar because of the limited space available in cars. Contrary to cars, buses have more space available for hydrogen storage, and therefore it is easier to equip them with a 350-bar storage tank. The advantage of a 350-bar storage tank is that it can be loaded more quickly and easily than a 700-bar storage tank. Moreover, a 350-bar storage tank shows overall better efficiency thanks to the lower pressure level, and a 350-bar storage tank is typically slightly cheaper (*32*). Therefore, a storage tank with a pressure of 350-bar is assumed in our model.

A benefit of the hydrogen fueling infrastructure is that it can be similar to the fueling infrastructure for diesel vehicles. At this location, two spots for refueling hydrogen vehicles are available. When the hydrogen level reaches 20% remaining (6 kilograms hydrogen), the vehicle finishes unloading its current entity and travels to the hydrogen station. A big advantage of compressed hydrogen is the short refueling time of just a few minutes (*19*, *33*). Multiple studies show a different number of minutes for refueling. The Hyundai hydrogen truck used here as a reference has a refueling time between 8 and 20 minutes, with an average of 14 minutes (*30*). The storage tank capacity also needs to be defined. The Hyundai hydrogen truck is capable of storing a little more than 30 kilograms of hydrogen (*30*). Little knowledge is available about how far vehicles can drive with how much hydrogen. Only reference information for commercial cars can be found. It is known that 1 kilogram of hydrogen allows a radius of 100 kilometers (*34*). In the model based on this assumption, the hydrogen consumption of the vehicles is calculated for driving from the QC to ASC, ASC to QC, and to the fuel station.

For Scenario 2, hydrogen vehicles, Experiment 22 provides the best results: 70 vehicles with a fuel time of 14 minutes and one spot available at the fuel station are required to maintain the same container throughput. As the simulation model incorporates 31.57% of all containers, the total answer is: 222 hydrogen vehicles and 3 spots available at the fuel station. It can also be seen that the number of spots available at the fuel/charging station seems not to influence the containers' flowtime, as the utilization percentages of the charging station is very low and the waiting time is negligible.

DISCUSSION AND CONCLUSION

Implementing a new vehicle fleet at terminals has huge impacts on operational performance and costs. Operational performance is tested by a simulation model and, from the results of all the experiments, it can be stated that more vehicles and charging stations are needed when battery vehicles are used instead of diesel vehicles. Also, more vehicles are needed when diesel vehicles are replaced by hydrogen vehicles. To maintain the same amount of container throughput, a scenario with battery vehicles needs 215 battery vehicles with a charging time of 30 minutes, and 32 spots available at the fuel station are required. In the case of hydrogen vehicles, 222 vehicles with a fuel time of 14 minutes are needed, and 3 spots need to be available at the fuel station. From this perspective, it can be concluded that renewable energy carriers could cause traffic consequences for operational performance, given the increase in the number of vehicles needed.

As an addition to this study, some cost calculations have been made on several assumptions, as the configuration of the new energy terminal equipment is known from the simulation model. From a scientifical point of view, these calculations contain too much uncertainty to be relevant. It can only be said that both the capital cost and the operational cost are cheaper for the hydrogen vehicles. Further research on costs, such as maintenance costs and so on, should provide a more detailed insight into the real total cost. The simulation model developed can assist terminal operators in their choices to invest in new zero-emission equipment by showing the operational consequences for the terminal.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: J.H.R. van Duin, C. van der Wijst and G.P. van Wee; data collection: C. van der Wijst; analysis and interpretation of results: C. van der Wijst; draft manuscript preparation: J.H.R. van Duin, C. van der Wijst, H. Geerlings. All authors reviewed the results and approved the final version of the manuscript.

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REFERENCES

1. Al-Ghussain, L. (2019). Global warming: review on driving forces and mitigation. Environmental *Progress & Sustainable Energy*, *38*(**1**), 13–21
2. United Nations. (2015). Paris Agreement. Retrieved from https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf
3. Brandon, N. P., & Kurban, Z. (2017). Clean energy and the hydrogen economy. *Philosophical Transactions Royal Society A*, 375:20160.
4. Dominković, D. F., Bačeković, I., Pedersen, A. S., & Krajačić, G. (2018). The future of transportation in sustainable energy systems: Opportunities and barriers in a clean energy transition. *Renewable and Sustainable Energy Reviews* (**82**), 1823–1838
5. Wang, N., Chang, D., Shi, X., Yuan, J., & Gao, Y. (2019). Analysis and Design of Typical Automated Container Terminals Layout Considering Carbon Emissions. *Sustainability* **2019** *11*, 2957
6. Hall, D., Pavlenko, N. and Lutsey, N. (2018). *Beyond road vehicles: Survey of zero-emission technology options across the transport sector*, The International Council on Clean Transportation. 11. Retrieved from: https://www.theicct.org/sites/default/files/publications/Beyond_Road_ZEV_Working_Paper_20180718.pdf
7. Lim, K., (2020). *Accelerating the Race to Zero Emission Shipping*, the World Economic Forum. Retrieved from: https://www.weforum.org/events/race-to-zero-dialogues-2020/sessions/accelerating-the-race-to-zero-emission-shipping
8. Bresser, D., Hosoi, K., Howell, D., Li, H., Zeisel, H., Amine, K., & Passerini, S. (2018). Perspectives of automotive battery R&D in China, Germany, Japan, and the USA. Journal of Power Sources, 382, 176–178
9. Ruiz, V., Pfrang, A., Kriston, A., Omar, N., Van den Bossche, P., & Boon-Brett, L. (2018). A review of international abuse testing standards and regulations for lithium ion batteries in electric and hybrid electric vehicles. *Renewable and Sustainable Energy Reviews* (**81**), 1427–1452.
10. Hache, E., Seck, G. S., Simoen, M., Bonnet, C., & Carcanague, S. (2019). Critical raw materials and transportation sector electrification: A detailed bottom-up analysis in world transport. *Applied Energy* (**240**), 6–25
11. Armaroli, N., & Balzani, V. (2016). Solar Electricity and Solar Fuels: Status and Perspectives in the Context of the Energy Transition. *Chemistry: A European Journal*, *22*(**1**), 32–57
12. Forrest, K. (2019). *Zero-Emission Heavy-Duty Vehicle Integration in Support of a 100% Renewable Electric Grid* (University of California). Retrieved from https://escholarship.org/uc/item/7z1885mz
13. Shkolnikov, E. I., Zhuk, A. Z., & Vlaskin, M. S. (2011). Aluminum as energy carrier: Feasibility analysis and current technologies overview. *Renewable and Sustainable Energy Reviews* (**15**), pp. 461
14. Sun, X., Li, Z., Wang, X., & Li, C. (2019). Technology Development of Electric Vehicles: A Review. *Energies*, *13*(**1**), 90
15. Schmidt, J., Meyer-Barlag, C., Eisel, M., Kolbe, L. M., & Appelrath, H. J. (2015). Using batteryelectric AGVs in container terminals - Assessing the potential and optimizing the economic viability. *Research in Transportation Business and Management* (17), 99–111
16. Hosseini, S. E., & Wahid, M. A. (2016). Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development. *Renewable and Sustainable Energy Reviews* (**57**), 850–866
17. Møller, K. T., Jensen, T. R., Akiba, E., & Li, H. wen. (2017). Hydrogen - A sustainable energy carrier. *Progress in Natural Science: Materials International*, *27*(**1**), 34–40
18. Sharma, S., & Ghoshal, S. K. (2015). Hydrogen the future transportation fuel: From production to applications. *Renewable and Sustainable Energy Reviews* (**43**), 1151–1158

19. Jordbakke, G. N., Amundsen, A., Sundvor, I., Figenbaum, E., & Hovi, I. B. (2018). *Technological maturity level and market introduction timeline of zero-emission heavy-duty vehicles*. Institute of Transport Economics, 29–34
20. Aué, J.-J. (2018). *De rol van Waterstof binnen de Energietransitie*. Inaugural speech, Hanzehogeschool Groningen. Retrieved from https://research.hanze.nl/ws/portalfiles/portal/24551976/Redeboekje_Jan_jaap_Au_.pdf
21. Xue, M., Wang, Q., Lin, B. Le, & Tsunemi, K. (2019). Assessment of Ammonia as an Energy Carrier from the Perspective of Carbon and Nitrogen Footprints. *ACS Sustainable Chemistry and Engineering, 7*(**14**), 12494–12500
22. Guo, J., & Chen, P. (2017). Catalyst: NH3 as an Energy Carrier. *Chem* (**3**), 709– 712
23. Miura, D., & Tezuka, T. (2014). A comparative study of ammonia energy systems as a future energy carrier, with particular reference to vehicle use in Japan. *Energy* (**68**), 428–436
24. MacFarlane, D. R., Cherepanov, P. V., Choi, J., Suryanto, B. H. R., Hodgetts, R. Y., Bakker, J. Ferrero Vallana, F.M., Simonov, A. N. (2020). A Roadmap to the Ammonia Economy. *Perspective 4*(**6**), 1186-1205
25. Fúnez Guerra, C., Reyes-Bozo, L., Vyhmeister, E., Jaén Caparrós, M., Salazar, J. L., & Clemente-Jul, C. (2020). Technical-economic analysis for a green ammonia production plant in Chile and its subsequent transport to Japan. *Renewable Energy* (157), 404–414
26. Walker, W. (1988). Chapter 6 Generating and screening alternatives. In *Handbook Systems Engineering: Craft issues and procedural choices*, 217–246
27. Pegden, C. D. (2008). Introduction to simio. *Proceedings - Winter Simulation Conference*, 229–235.
28. Sargent, R. G. (2013). Verification and validation of simulation models. *Journal of Simulation*, *7*(**1**), 12–24
29. Robinson, S. (2012). Tutorial: choosing what to model - conceptual modeling for simulation. Proceedings of the 2012 Winter Simulation Conference, 1–12
30. FuelCellsWorks. (2020). *World's First Fuel Cell Heavy-Duty Truck*, Hyundai XCIENT Fuel Cell, Heads to Europe for Commercial Use - FuelCellsWorks. Retrieved from https://fuelcellsworks.com/news/worlds-first-fuel-cell-heavy-duty-truck-hyundai-xcient-fuelcell-heads-to-europe-for-commercial-use/.
31. Gurz, M., Baltacioglu, E., Hames, Y., & Kaya, K. (2017). The meeting of hydrogen and automotive: A review. *International Journal of Hydrogen Energy*, *42*(**36**), 23334–23346
32. Baetcke L. & Kaltschmitt, M. (2018). Hydrogen Storage for Mobile Application: Technologies and Their Assessment. In C. Azzaro-Pantel (ed.), Hydrogen Supply Chains, Academic Press, 167-206.
33. Stetson, N. T., McWhorter, S., & Ahn, C. C. (2016). Introduction to hydrogen storage. *Compendium of Hydrogen Energy* (**20**), 3–25).
34. Airliquide, (2020). How is hydrogen stored? *Air Liquide Energies*. Retrieved from https://energies.airliquide.com/resources-planet-hydrogen/how-hydrogen-stored