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Investigation of the impact of a solar panel system installed on an heavy-duty truck trailer on fuel consumption at the ZalaZONE test track

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ABSTRACT

This study evaluates the impact of a solar panel system installed on a heavy-duty truck (HDV) trailer on fuel consumption, tested at the ZalaZONE track. Two vehicles were assessed – diesel-powered and an liquefied natural gas (LNG) powered truck, with the latter equipped with solar panels. Over five days, the solar system powered cabin electronics, reducing idle time and fuel use. While fuel and carbon dioxide (CO_2) savings were observed, performance was limited by battery charge and sunlight exposure. The results show potential for up to 10% fuel savings, demonstrating the system's feasibility for reducing emissions in long-haul transport, though further optimization is needed.

Keywords: solar panel, transportation, CO_2 emission reduction, heavy-duty trucks.

INTRODUCTION

Sustainability, environmental protection, and digitalization are key trends that continuously reshape the landscape of transportation and logistics. Carbon dioxide (CO_2), the primary greenhouse gas (GHG) produced by human activities, naturally exists in environments where human intervention can easily disturb the balance, such as during the extraction and use of fossil fuels [1]. The trucking industry plays a major role in GHG emissions, contributing more than 2,200 Mt of CO_2 annually. Transportation overall is responsible for around 5–6% of global GHG emissions, and accounts for over 24–25% of CO_2 emissions [2]. The European Commission's [3] report from 2023, "The European Green Deal," confirms this level of emissions and highlights that nearly 95% of the EU's vehicle fleet still runs on internal combustion engines (ICEs), primarily dependent on imported fossil fuels. Globally, China (over 9,500 million tons) and the United States (over 5,000 million tons) remain the top emitters. In Europe, Germany (over 900 million tons) leads GHG emissions, followed by the United Kingdom (470 million tons) and France (460 million tons), with the energy, industrial, and transport sectors being the main contributors [4]. Gunawan and Monaghan's [5] study identifies the heavy-duty vehicle (HDV) sector as one of the most difficult to regulate when it comes to reducing GHG emissions in the transport industry.

There are several alternatives for HDV powertrains that either reduce or eliminate greenhouse gas emissions. Hydrogen propulsion and battery technology offer potential, but each has limitations. Hydrogen can lower emissions significantly, but its high costs, non-green production, and low fuel energy density hinder its viability as a full diesel replacement [6, 7]. Battery efficiency depends on factors like energy source, charging time, and infrastructure, which remains insufficient in HDV sector [8, 9]. Natural gas technology, especially LNG, is a promising alternative, reducing harmful emissions and offering up to 10% fewer greenhouse gases than conventional fuels, making it suitable for long-distance transport [10, 11].

The transport sector continues to exhibit the lowest share of renewable energy consumption within the overall energy landscape, with over 95% of its energy demand still met by oil and petroleum-based products, while biofuels and renewable electricity accounted for less than 4% in 2018. Some countries have made incremental progress in integrating renewable hydrogen and synthetic fuels into transport systems, yet their contribution remains marginal at a global level. In 2018, road transport constituted approximately 75% of global transport energy consumption, with passenger vehicles accounting for over two-thirds of this share. Conversely, the rail sector, which is the most electrified mode of transport, derived an estimated 11% of its total energy use from renewable sources – primarily renewable electricity and biofuels – by 2019. In recent years, targeted policies have sought to strengthen the connection between renewable energy generation and transport sector [12].

The continuous advancement of technology has led to a reduction in fossil fuel consumption through the integration of clean energy sources, with solar energy offering the greatest potential among renewable options worldwide. By incorporating additional power sources, fossil fuel use can be significantly reduced, resulting in extended driving ranges, longer refuelling intervals, fewer emissions, and a longer lifespan for internal combustion engines [13, 14]. Enhanced fuel efficiency during idle periods, particularly when trucks are at rest, can also lower transportation costs and cut carbon dioxide emissions. Large line-haul trucks often idle overnight to keep fuel and engines warm, power cabin appliances, and maintain comfortable temperatures during driver rest periods. Additionally, trucks idle at ports, delivery sites, border crossings, and loading zones during the workday. Given that fuel represents 38% of total operational costs for long-haul trucks, it remains the second-largest cost per mile [15].

MATERIALS AND METHODS

The measurements were conducted using two heavy-duty trucks: one being a conventional diesel-powered tractor and trailer, and the other an alternative LNG-powered tractor and trailer combination. Both vehicles were sourced from the same Original Equipment Manufacturer (OEM), each equipped with a 13,000 cm³ engine, a 12-speed automatic transmission, and similar-sized tires. The vehicle assemblies included box-structured semi-trailers, with the LNG variant featuring a solar-powered energy supply system (SolarOnTop System) comprising a 20 m² (a total of 10 solar panels) configuration. This system was connected to a 4 kW/h lithium ($LiFePO_4$) battery and a dedicated control unit (see Figure 1).

The purpose of the solar panel system in the current heavy-duty vehicle is to supply power to the electrical consumption within the driver's cabin. During transportation, drivers often spend their rest periods inside the cabin, where air conditioning, heating, and the charging and powering of personal electronic devices may be required. Typically, this electrical demand is met by the vehicle's starter battery. If the battery's charge drops below a certain level, the vehicle's engine is started and idled, allowing the generator to recharge the battery. Internal combustion engines generally operate inefficiently under idle conditions and low loads, further compounded by the

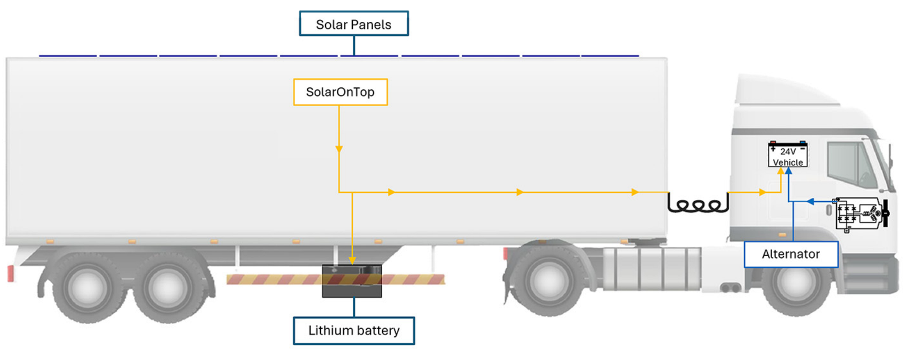

Figure 1. The SolarOnTop system installation – conception visualization [16]

inefficiency of the generator, which increases the fuel consumption required to produce a given amount of electricity. The aftermarket-installed battery and solar panel system is connected to the cabin's electrical network, allowing the energy generated by the solar panels to reduce the engine's idling time, thereby decreasing fuel consumption, CO_2 emissions, and engine wear. According to the manufacturer, the system's return on investment is approximately 3 years and fuel saving is 2000 liters per year, depending on efficiency and utilization. This publication aims to investigate the potential reduction in CO_2 emissions achievable through the solar panel system.

The heavy-duty vehicles were stationed at the ZalaZONE test track (www.zalazone.hu, accessed on 10 October 2024) in Zalaegerszeg for five days, undergoing various consumption measurements. The entire testing cycle featured diverse environmental conditions, focusing primarily on highway driving modes and the simulation of rural road transportation, complemented by hills, slopes, and urban settings (Figure 2).

The five-day testing series was divided into six distinct test types, each incorporating various interconnected systems and test cases. This approach was designed to closely simulate real-world freight transport operations and ensure a comprehensive representation of practical scenarios. During the tests, the tractors covered approximately 500 kilometers. Due to varying environmental conditions, the total consumption amounted to 166 liters of diesel and 147 kilograms of LNG, revealing an approximate 14% difference in fuel efficiency. The track elements for each test day were as follows:

- T1: motorway + rural road (public road tests),
- T2: rural road (public road tests),
- T3: smart city zone (urban area tests),
- T4: motorway + rural road (public road tests),
- T5: hill (ascent/slopes) & motorway + rural road (public road tests),
- T6: high speed – handling course (specific consumption analysis).

Overall, the analysis consisted of 75% highway and motorway driving, 10% urban driving, 5% uphill scenarios, and the remaining 10% focused on consumption-specific tests across the test cases ranging from T1 to T6.

The examination of the solar panel system was not directly linked to the measurements conducted on the test track; the key factor was that the truck was outdoors during the day, allowing the solar panels to be exposed to sunlight. The data from the aftermarket-installed solar panel system could not be retrieved through the truck's standard communication interface, the Fleet Management System (FMS) Gateway. Instead, the system manufacturer collects the data online, and the information can be downloaded after logging into their website. While numerous performance data points for the solar panels are available, most of them are presented without units and are labeled with custom descriptors. Unfortunately, the company did not provide more detailed information about these values, meaning only the amount of energy generated by the solar panels is reliably known, while the precise voltage, current, and charge levels are not. However, we recorded environmental factors (Table 1), thus parameters such as temperature (°C), humidity (%), wind

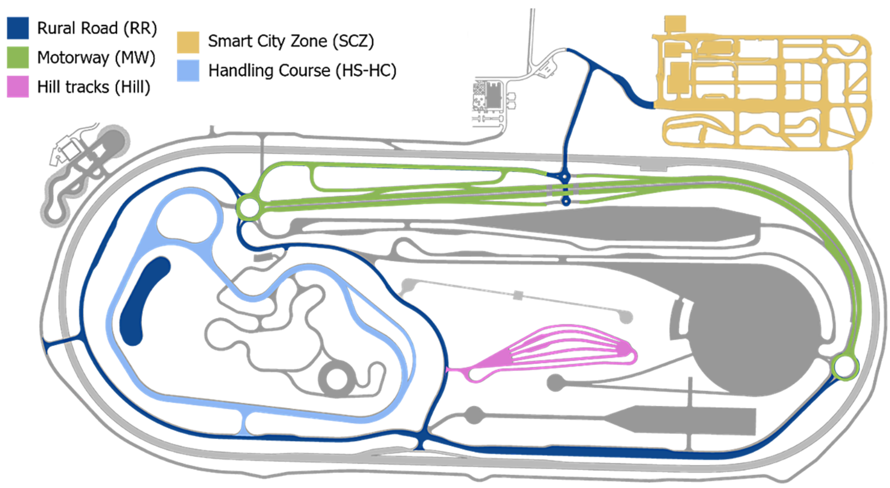

Figure 2. The map of the ZalaZONE proving ground and the used test tracks

Table 1. Environmental factors during the measurement

Date	Temperature (C°)	Humidity (%)	Wind speed (km/h)	Wind direction	Luminous intensity (LUX)
2023.09.04.	24.6	41.8	15.5	NW	89400
2023.09.05.	23.1	55	15	NW	57850
2023.09.06.	24.7	54.5	2.5	NW	61050
2023.09.07.	23.6	53.5	1.5	N	68000
2023.09.08.	21	61.5	2	NE	55700

speed (km/h), wind direction, and light intensity (LUX) were consistently monitored.

RESULTS AND DISCUSSION

During the five-day test, the solar-equipped truck spent the nights in a garage, only being exposed to sunlight during the test periods. Therefore, the solar panels were able to charge exclusively during these times. The tests were conducted in early September, meaning the sun was consistently present in the sky throughout the measurements, with mostly clear weather, allowing direct sunlight to reach the solar panels. According to the manufacturer's data, the maximum instantaneous total power output of the 10 installed solar panels can reach up to 4.3 kW.

Among the data retrieved from the solar panel's online system, the battery charging power was crucial for calculating how much fuel would have been consumed if the solar panels did not generate the corresponding amount of electricity. Table 2 summarizes the quantities of electricity produced from solar energy. The average instantaneous power values fall by an order of magnitude below the manufacturer's specified maximum output.

The low performance of the solar panels can be explained by the instantaneous current levels and the battery charge status (Figure 3). At the start of each test day, when the truck was brought out of the garage, the battery charge immediately jumped to 100%, regardless of its discharge level during storage. This phenomenon can be attributed to the fact that the charge status is determined by voltage, and as soon as the solar panels begin charging the battery, the system receives a voltage sufficient to register a 100% charge. The actual state of charge of the battery can be inferred from the current levels. In the downloadable data from the online system, it was only indicated that the data series represented current, but it lacked a specified unit, which is why this is not reflected on the diagram. The current levels were significantly higher at the beginning of the testing period and then dropped to nearly half, despite the tests starting in the morning when the sunlight intensity was lower than later in the day. This reduction in current likely occurred because the battery became fully charged. Based on this, the low average performance of the system can be explained. If the test days had started with a fully discharged battery, the solar system would have been able to charge at a higher power level for a longer duration.

According to the data provided by the manufacturer of the solar system, producing 1 kWh of electrical energy requires burning 1.2 liters of diesel fuel, which corresponds to approximately 1 kg in mass. For LNG, no specific value is defined, so this can only be estimated based on calculations. However, Kulikov et al.'s [17] publication discusses the fuel consumption of diesel

Table 2. Results of the solar panel system during the tests

Date	Duration (h)	Energy produced (Wh)	Average performance (W)
2023.09.04.	10	2793	279.3
2023.09.05.	9.33	3262	349.6
2023.09.06.	7.25	2425	334.5
2023.09.07.	6,83	3180	465.6
2023.09.08.	3	1863	621
∑	36.41	13523	371.4

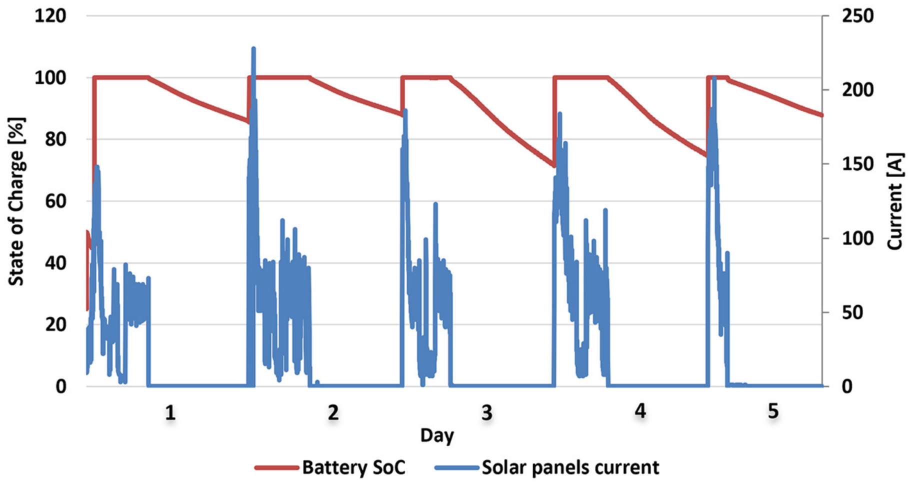

Figure 3. Battery state of charge and voltage of the solar panel system during the test days

and LNG-powered heavy-duty vehicles, revealing that a diesel engine at idle, under low load, consumes approximately 300 grams of fuel to produce 1 kWh of mechanical energy. The corresponding diagrams are shown in Figure 4.

If the generator's efficiency is 30%, the manufacturer's value can be derived, indicating that 1 kg of diesel fuel can generate 1 kWh of electricity. In the case of LNG, the efficiency value is approximately 250 g/kWh. If electricity is also produced with a 30% efficient generator, then 0,83 kg of fuel is required to generate 1 kWh of electricity. Based on the carbon dioxide equivalent of the fuels, the amount of CO_2 released from burning 1 kg of fuel can be calculated for diesel (see Equation 1) and LNG (see Equation 2) types [18].

In case of LNG fuel:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (1)$$

$$(CH_4 \rightarrow 16{,}04\ g/mol,\ CO_2 \rightarrow 44{,}01\ g/mol = $$
$$= 16\ g\ CH_4 \rightarrow 44\ g\ CO_2,\ 1\ kg\ CH_4 \rightarrow 2{,}75\ kg\ CO_2)$$

In Equation 1 methane (CH_4) is the main component (CH_4 = 16,04 g/mol, CO_2 = 44,01 g/mol, where 16 g CH_4 becomes 44 g CO_2 emission), it follows that from the combustion of 1 kg CH_4 becomes 2,75 kg CO_2 emission.

In case of Diesel fuel:

$$C_{16}H_{34} + 49/2O_2 \rightarrow 16CO_2 + 17H_2O \quad (2)$$

$$(C_{16}H_{34} \rightarrow 226{,}445\ g/mol,\ 16CO_2 \rightarrow$$
$$\rightarrow 704{,}16\ g/mol = 226{,}445\ g\ C_{16}H_{34} \rightarrow$$
$$\rightarrow 704{,}16\ g\ CO_2,\ 1kg\ C_{16}H_{34} \rightarrow 3{,}11\ kg\ CO_2)$$

In Equation 2 diesel ($C_{16}H_{34}$) is the main component ($C_{16}H_{34}$ = 226,445 g/mol, $16CO_2$ = 704,16 g/mol, where 226,445 g $C_{16}H_{34}$ becomes 704.16 g CO_2 emission), it follows that from the combustion of 1kg $C_{16}H3_4$ becomes 3.11 kg CO_2

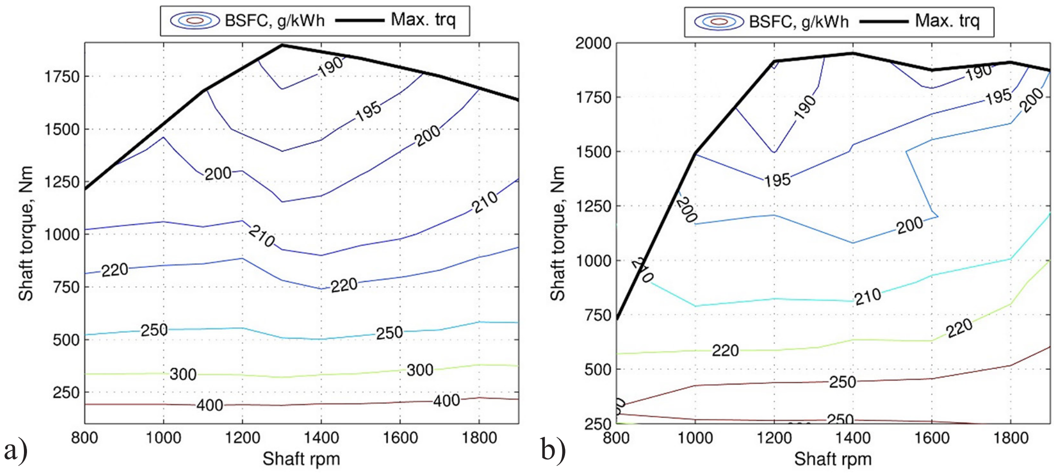

Figure 4. Brake-specific fuel consumption (BSFC) maps in different heavy-duty truck powertrains: (a) Diesel BSFC in the literature, (b) LNG BSFC in the literature

Table 3. Diesel and LNG CO_2 emission savings

Details	Diesel	LNG
Idling consumption [g/kWh]	300	250
Alternator efficiency [%]	30	30
Fuel equivalent [kg/kWh]	1	0,83
CO_2 emission [kg CO_2/kg fuel]	3.11	2.75
CO_2 saving [kg/kWh]	3.11	2.28

emission. Based on the Equation 2, 1 liter of diesel produces 2.61 kilograms of CO_2, at a density of 840 kg/m^3 of diesel [18]. Based on this, the savings value associated with the two types of fuel can be determined, indicating how much carbon dioxide emissions 1 kWh of electricity generated from solar panels helps to mitigate in the environment. These values are summarized in Table 3.

CONCLUSIONS

During the five days of testing, the solar panel system was able to generate 13.5 kWh of electricity, which, according to preliminary calculations, results in a savings of 11.2 kg of fuel for the LNG tractor, equivalent to 30.78 kg of carbon dioxide emissions. If this system had assisted in the energy supply of the diesel tractor, it would have resulted in a savings of 13.5 kg of fuel and 41.99 kg of carbon dioxide. Annually, this translates to a reduction of 2.25 tons of carbon dioxide for the LNG and 3.06 tons for the diesel. Based on the measurements, the solar panel system could not continuously generate electricity due to the battery charge status and the truck was not exposed to sunlight throughout the entire day. Therefore, the manufacturer's claim of 7 tons/year of carbon dioxide savings for the diesel tractor is considered realistic. The LNG drive is fundamentally a more environmentally friendly solution; calculations indicate that the solar panel system can achieve a 26% lower carbon dioxide savings compared to the values associated with diesel.

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REFERENCES

1. Nunes LJR. The Rising Threat of Atmospheric CO2: A Review on the Causes, Impacts, and Mitigation Strategies. Vol. 10, Environments - MDPI. MDPI; 2023.
2. Krause J, Arcidiacono V, Maineri L, Broekaert S, Fontaras G. Calculating heavy-duty vehicle CO2 emission reduction costs for Green Deal scenarios: Extension of the DIONE model. In: Transportation Research Procedia. Elsevier B.V.; 2023; 2597–603.
3. European Commission. European Green Deal: Commission proposes 2030 zero-emissions target for new city buses and 90% emissions reductions for new trucks by 2040. Strasbourg; 2023 Feb [cited 2024 Mar 26]. Available from: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_762
4. Anderhofstadt B, Spinler S. Preferences for autonomous and alternative fuel-powered heavy-duty trucks in Germany. Transp Res D Transp Environ. 2020; 1: 79.
5. Gunawan TA, Monaghan RFD. Techno-econo-environmental comparisons of zero- and low-emission heavy-duty trucks. Appl Energy. 2022; 15; 308.
6. Osorio-Tejada JL, Llera-Sastresa E, Scarpellini S. Liquefied natural gas: Could it be a reliable option for road freight transport in the EU? Vol. 71, Renewable and Sustainable Energy Reviews. Elsevier Ltd; 2017; 785–95.
7. Van Kranenburg K, Van Delft Y, Gavrilova A, De Kler R, Schipper C, Smokers R, et al. E-fuels: towards a more sustainable future for truck transport, shipping and aviation. 2020 [cited 2024 Jun 5]. Available from: https://www.tno.nl/publish/pages/3735/vankranenburg-2020-efuels.pdf
8. Cunanan C, Tran MK, Lee Y, Kwok S, Leung V, Fowler M. A review of heavy-duty vehicle powertrain technologies: diesel engine vehicles, battery electric vehicles, and hydrogen fuel cell electric vehicles. Clean Technologies. MDPI; 2021; 3: 474–89.
9. Sugihara C, Hardman S, Kurani K. Social, technological, and economic barriers to heavy-duty truck electrification. Research in Transportation Business and Management. 2023; Dec 1: 51.
10. Rodrigues Teixeira AC, Borges RR, Machado PG, Mouette D, Dutra Ribeiro FN. PM emissions from

heavy-duty trucks and their impacts on human health. Atmos Environ. 2020; Nov 15: 241.

11. Pfoser S, Schauer O, Costa Y. Acceptance of LNG as an alternative fuel: Determinants and policy implications. Energy Policy. 2018; Sep 1(120): 259–67.
12. SLOCAT. Tracking Trends in a Time of Change: The Need for Radical Action Towards Sustainable Transport Decarbonisation SLOCAT Transport and Climate Change Global Status Report 2 nd edition. 2021. Available from: www.slocat.net
13. Popa DM, Popa D, Tabacu S. Heavy-duty vehicles with solar panels as a regenerative power source. IOP Conf Ser Mater Sci Eng. 2024; 1311(1): 012032. Available from: https://iopscience.iop.org/article/10.1088/1757-899X/1311/1/012032
14. Ifaei P, Khiabani H, Piran MJ, Yoo CK. Techno-econo-environmental feasibility of retrofitting urban transportation system with optimal solar panels for climate change mitigation – A case study. J Clean Prod. 2020; Apr 1: 251.
15. Sheth K, Patel D, Swami G. Reducing electrical consumption in stationary long-haul trucks. Open Journal of Energy Efficiency. 2024; 13(3): 88–99. Available from: https://www.scirp.org/journal/doi.aspx?doi=10.4236/ojee.2024.133006
16. IM Efficiency. SolarOnTop Empowering trucks with solar energy. 2024 [cited 2024 Sep 25]. Available from: https://imefficiency.com/solarontop
17. Kulikov I, Kozlov A, Terenchenko A, Karpukhin K. Comparative study of powertrain hybridization for heavy-duty vehicles equipped with diesel and gas engines. Energies (Basel). 2020; 13(8).
18. M.E. Schwarzkopf. Investigating the introduction of alternative tractor-trailers in Hungary [Thesis]. [Budapest, Hungary]: Budapest University of Technology and Economics; 2019.