DEVELOPMENT, CONSTRUCTION AND FIVE-YEAR USAGE OF A 100% SOLAR ELECTRIC CARGO TRICYCLE IN HUNGARY

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ABSTRACT

This article describes the development and design of a sustainable solar electric cargo tricycle in Hungary, Europe, as well as the implementation experience and results of its five-year-long operation powered solely by onboard solar energy. The authors examined current low-consumption transportation methods, electric vehicles, and their suitability for solar usage in sustainable transport systems. Conclusions were drawn regarding the design, sizing, and optimisation of solar vehicles for onboard solar energy utilisation. A total distance of 24,748.4 km was covered with 1,686 kWh of total energy consumption, according to onboard measurements, demonstrating 100% solar-powered operation from 2017 to 2022. The sun provides sufficient energy for daily passenger and cargo transport with fully onboard-generated solar power even in Central Europe, provided that a lighter and slower solar-powered electric tricycle is developed instead of high-consumption cars. Apart from the inability to reach distant destinations quickly, the vehicle functions similarly to automobiles.

Keywords: *Sustainable transportation, solar electric cargo tricycle, onboard solar energy, autonomous solar electric mobility.*

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INTRODUCTION

As Earth is a finite planet, humanity must find solutions in transportation that do not rely on fossil fuels for planes, ships, petrol, gasoline, and diesel cars. Hydrocarbon reservoirs are not unlimited, nor are the absorbing capacities of the atmosphere, oceans, biosphere, and other parts of natural systems necessary for the future of civilisation and the biosphere. Burning fossil fuels pollutes the air and plays a critical role in overconsumption, according to commonly accepted research, as presented in Targets and Options for Reducing Lifestyle Carbon Footprints [[1]], the Framework Convention on Climate Change [[2]], and the Emissions Gap Report [[3]] by the United Nations. If the current energy demand for transportation cannot be supplied with renewable energy sources, a sustainable strategy should reduce this demand, and needs must be urgently adjusted. For example, cars or air travel consume approximately 80 to 110 kWh per 100 passenger-km from fossil fuels [[4]], contributing to significant consumption and pollution considering that each trip typically covers hundreds or thousands of kilometres. Therefore, the utilisation of these technologies should be reduced to a sustainable level, ideally approaching zero [[5]].

For daily transportation, the current fossil-fuelled car concept needs to be changed. Renewable sources, such as bioenergy, water, sun, and wind, can be used with the help of transformer technologies through central or regional fuel networks, such as biofuel, electricity in the grid, or hydrogen gas. However, these fuel networks face several crucial problems. First, renewables can only be added in small quantities as supplementary inputs, partially mixed as in the case of E5 and E10 petrol in Europe. Even with widespread use of electric, hydrogen, or biofuel cars, the high level of consumption remains or increases, and the current or growing demand cannot be met with the capacities of renewable energy sources [[6]]. Furthermore, there are problems with storing such large quantities of energy, e.g., battery pollution, hazardous waste, and risky hydrogen technologies. The high power demand during charging is also incompatible with current infrastructure on a full scale, not to mention that infrastructure development requires enormous investment. Ultimately, the system remains highly centralised, or it introduces dependence on mineral resources such as lithium, reducing the security of the supply chain. Centrally produced renewable energy can cover only a small percentage of demand, e.g., biofuels for the agriculture sector and hydrogen for buses with a limited number of stations, but it does not represent a sustainable or practical strategy for passenger cars. There are pilot projects on solar supply for cars where PV panels are placed on rooftops, although inverters and chargers are controlled according to solar production rather than demand [[7]]. The main problem with such a strategy is the usage and hazardous life cycle of a significant number of solar panels and high battery capacity to cover the increased consumption of electric cars. Installed charging capacity must also be significant—e.g., 5 kW or 22 kW in AC (alternating current), or 50 kW and 150 kW in DC (direct current)—which results in technical problems in the local grid [[8]].

Accelerating high weight to high speed results in increased consumption. According to the Jevons paradox, energy saving cannot simply be achieved through efficiency improvements [[9]]. Therefore, the authors searched for a solution that can be supplied by renewable energy sources and that has low consumption. Local solutions have traditionally included human and horse muscle power, but for the 21st century, photovoltaic technologies also represent an option. These allow onboard energy generation using 100% renewable sources or grid-compatible methods, where connection and consumption require only small-scale power and energy capacity. This is why SunSnail (in Hungarian, NapCsiga), an environmentally sustainable, cost-effective, solar-powered cargo transport solution based on a three-wheeled small vehicle, was developed in Hungary.

METHODS OF PLANNING A SOLAR VEHICLE

After following and understanding the logical steps of the Introduction (1), the following aim was declared: the consumption of present transportation methods should be reduced not only by small percentages but also by an order of magnitude. During the research, all modes of inland transportation were classified according to their consumption—from micro and small to medium consumption range—the possibility for energy balance, and their functionality for personal and cargo transport based on international data sources. In the planning phase, solar energy and its availability were determined; energy calculations were made, and several aspects, such as economics, ergonomics, and functionality in design and sizing, were considered. Results and discussions rely on physical implementation, the experience of five years of usage, and databases from measured parameters.

CALCULATIONS, DESIGN, SIZING AND IMPLEMENTATION

Energy calculations and considerations, design of solar energy supply and usability, and sizing and implementation of a solar vehicle are detailed in sub-sections 3.1 to 3.4.

INTERNATIONAL OVERVIEW OF INLAND VEHICLES WITH SMALL CONSUMPTION FOR POSSIBLE SOLAR ENERGY SUPPLY

Inland transportation has several options with small energy consumption. These vehicles are classified according to their micro–small–medium unit consumption range [[4]], their possibility for energy balance with renewable energy sources, and their functionality for personal and cargo transportation. Their usage is most convenient in combination, as they are strong in one function and weaker in others.

Bicycles operate with human power, have micro consumption (renewable), and are effective for small distances and small cargo capacity, with a high degree of independence in mobility. However, depending on age and fitness, they can be inconvenient in rainy, windy, or snowy weather conditions [[10]].

Electric bicycles and electric scooters are efficient for small to medium distances and have slightly greater load-carrying capacity, even for passengers, but are still weather-dependent. Cargo electric bicycles can be very efficient, and electric bikes with trailers can be even more practical. The specific consumption for electric assistance is less than one kWh per 100 km, which can be supplied by solar power mainly with the help of a grid-tied system, since onboard solar charging is minimal because of the small available surface area [[11]].

Walking uses muscle power for short distances, with micro and ultra-light cargo capability, although it is a fundamental daily transportation method.

Horse riding and horse carriage rely on animal power (1–2 kW) for short to medium distances, with the possibility for cargo load, small to medium consumption (additional effort and energy for animal care), and parking difficulties in cities.

Train and other efficient public transportation have small to medium consumption of about 3 to 10 kWh per 100 passenger-km, which is very efficient. Although electric trains run only to fixed destinations and are limited to individual cargo transport (suitcases), they are the best option for long-distance travel at high speed. Traditional electric trains consume renewable energy according to its proportion in the national electrical grid. Interestingly, tiny trains can also be fitted with solar panels on their top, as was done in an experiment in Hungary [[12]].

Electric cargo and passenger 3-4-wheel mopeds require medium consumption (maximum 4–5 kWh/100 passenger-km), which can still be supplied by renewable energy sources. They can cover medium distances, especially far from railway stations, even in rural areas. Load capacity is up to a few hundred kilograms, and cargo volume is up to 1,500 litres. They may be weatherproof, although speed is limited to 25–45 km/h maximum. They are permitted to carry passengers, even adults, not only a single child as is the case for bicycles in Hungary. A market gap exists for low-consumption, multipurpose electric vehicles in developed, car-based societies. Four-wheel types such as golf carts are designed mainly for passenger transport with small cargo capacity [[13]]. They may have a flat roof on which solar panels can be installed, but the surface is insufficient to support stand-alone operation, as in the USA [[14]]. Three-wheel types achieve lower speed, around 25 km/h, providing increased safety and reduced consumption. As of August 2023, a few similar examples exist among electric tricycles and cargo tricycles. Even the few European models are based on components produced in Asia. Some of them are offered with a solar panel on the top as an option in Romania [[14]] and Austria [16], available without a closed cabin or cargo box.

The solar cargo tricycle SunSnail is unique among 3-wheel cargo vehicles with a closed cabin and cargo box, as it demonstrates 100% solar-powered and autonomous operation. The first prototype, designed and constructed in 2017 for the Researchers' Night at Edutus University, has been running for five years, carrying cargo and producing electricity with solar panels installed on the roof and sides. The second prototype was further developed in 2022; both are also used as research vehicles (Fig. 1). They serve educational purposes. Furthermore, daily updates and the latest news are shared on social media [[17]].

Figure 1. Solar cargo tricycle prototypes named SunSnail in Hungary

There are three similar solar tricycle solutions worldwide at present. The one in China is less practical since it does not have a fixed cargo box and door. All sides are made of solar panels, which can be opened but only into a horizontal position [[18]]. The other example with a fixed cargo box is made in India, but the cabins for drivers and passengers are open [[19]]. The general direction of developing solar-powered tricycles and mopeds appears sustainable, convenient, and practical: even 100% solar operation can be achieved in the long run. Commercialisation has started in Asia with different constructions of solar passenger tricycles [[20]].

Specialised automobiles optimised for high speed are designed for global solar car competitions, where the main goal is to reach high speed using solar energy. As they must consume very little—small to medium—and be covered with photovoltaic panels, these vehicles lose functionality in all other aspects (e.g., ergonomics, economics, parking, safety, commercial value). Most of them are impractical for daily personal or cargo transport [[21]]. Some exceptions are ergonomic but expensive [[22]].

Smaller electric cars shared in cities by rental services have medium to high consumption (10–20 kWh/100 passenger-km), which is lower than current cars but higher than mopeds. They can be charged under solar panels in parking areas. As expectations for distances and speed in cities are not so high, mopeds and tricycles with reduced consumption should be preferred [[23]].

Smaller and lighter cargo vans, trucks, or buses with solar panels reach consumption parity (over 20–30 kWh/100 passenger-km) [[24]]. There are development efforts to install solar panels on electric vans or trucks, but they have not reached energy balance because of their medium to high consumption. Some smaller ones with flat surfaces exist as pilot projects with 7.5 kW motors in Germany [[25]].

DESIGN AND SIZING CONSIDERATIONS OF ONBOARD SOLAR VEHICLES

This section consists of considerations and examinations regarding the design and sizing of fully onboard-generated solar-powered vehicles in Hungary. Comprehensive ideas were formulated at the beginning of the research project in 2017 [[17]].

ENERGY PERFORMANCE CONSIDERATIONS

Firstly, some expectations are stated about solar-powered vehicles, such as low or moderate speed, low self-weight, low consumption, low dependency on the electrical grid or even long-term grid-off operation, medium capacity for energy storage, low emissions and waste even over the whole life cycle, high safety in traffic, the ability to carry large and heavy loads, and the presence of large and flat surfaces. The authors expected not only percentage improvements but also multipliers in these properties compared to cars.

SURFACE OF THE VEHICLE

A cargo tricycle was chosen because 5 m² of commercial photovoltaic panels can be easily placed on it. At the same time, it has a closed cab, which is essential due to Central European weather. For daily usage in Hungary, electric cargo tricycles are not common but have legal status as vehicles in the L2e category. These tricycles have electric motors rated from 500 W to 2,500 W, mainly between 1,000 W and 1,500 W. They can carry a few hundred kilograms in addition to their self-weight, yet their total weight is still much lower than that of electric cars. Solar panels can be considered fixed loads on the vehicle. Some cargo tricycles are produced with a closed cargo box, which provides relatively large flat surfaces for installing solar panels. The rear cargo area can be used as usual despite the solar panels, and the doors can be opened easily.

The electric power consumption of the 1,500 W vehicle is only a few hundred watts on average, which is consistent with the capacity of the battery (3–4 kWh) and with the average daily charge of the solar panels (0.5–1.2 kWh). It consumes 4–5 kWh per 100 passenger-km, so travelling 20–40 km requires 1–2 kWh per trip every 1–2 days. This amount of energy is small enough for problem-free charging from the electrical grid but can also be supplied with solar panels for grid-off situations. It requires limited battery capacity within the range of solar energy production, amounting to a few kWh depending on the battery type. The authors state that speed should preferably remain around 20–30 km/h for individual passenger and cargo transportation according to sustainability. Besides lower consumption, slower and lighter vehicles increase traffic safety and help maintain the stability of a three-wheel vehicle.

AMOUNT OF AVAILABLE SOLAR ENERGY

Solar energy is by no means infinite; consequently, analysing solar power and its availability is the basis of the 100% solar-operation strategy in electric mobility. Considering the efficiency of solar panels, a few hundred watts can be expected from three solar panels. If solar panels are installed on the surface of the vehicle, solar power is also utilised while driving. However, during parking, it charges the batteries. Professional measurements and big data analysis confirmed two simple rules: the sun does not shine at night due to daily periodicity, and it provides several times less energy in winter than in summer due to seasonality.

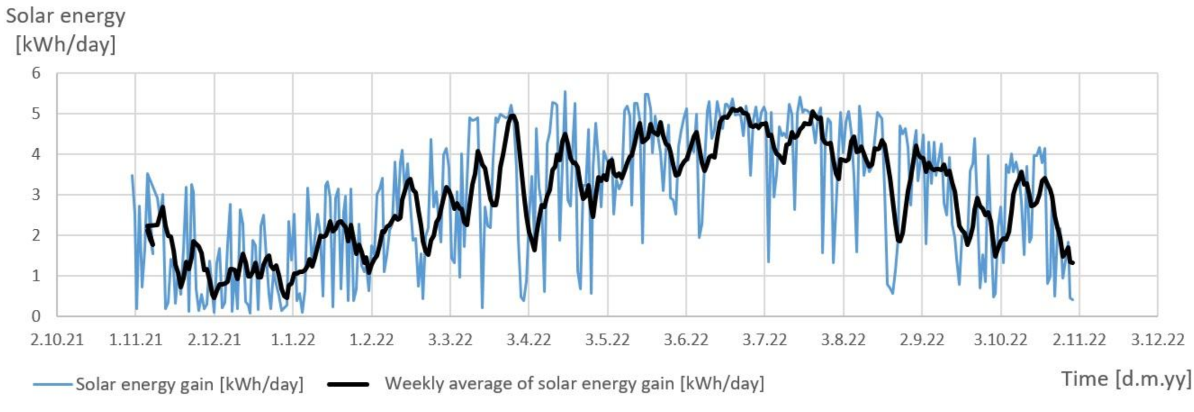

Figure 2. Daily solar energy production potential [kWh] of a 1 kW peak solar system during a year (blue) and weekly average (black) at Edutus University (North 47.5847851, East 18.3982176)

Daily solar energy production potential [kWh/day] was measured in a 1 kW peak system with optimal orientation and slope during a year, and the weekly average was analysed while preparing for solar operation (Fig. 2). AGM (absorbent glass mat), gel, or lithium batteries can manage daily fluctuation, but capacity must be estimated with attention to seasonality. The darkest weeks in winter provide ten times less daily energy than standard summer days. An average daily charge of 1.2–2 kWh can be expected in summer on the vehicle, and 0.5–0.8 kWh/day may be collected in winter, at least for self-consumption. The main characteristic of the daily charge can be estimated by the actual incoming energy until 10 a.m., the local weather forecast, and the consumption or length of the previous day’s trip. The authors planned 100% solar operation under the yearly average value of solar energy production from November until February with limited usage. This comes naturally if the driver lives an eco-friendly lifestyle. Demand is reduced in winter, but 50–60 km/day is achievable in summer. To reach 5,000 km/year with 100% onboard solar operation, it is useful to have some destinations without strict timing, so scheduling can be optimised within 1 or 2 days. The first SunSnail is a 100% solar version that has been operating since 2017, and in the current year, the second version was developed with an additional grid charge option for winter operation, battery protection, and institutional usage [[26]].

ORIENTATION OF THE SOLAR PANELS

Solar panels deliver maximum performance only when they are precisely perpendicular to the sun's incoming rays and the sky is clear. These conditions cannot be met in a moving vehicle. Irradiation is reduced by clouds, shadows, rain, or at dawn. However, the solar panels are installed on different vehicle surfaces, assuming that at least one of them may have a favourable orientation towards the sun.

To increase solar utilisation, the solar panels can be positioned facing the sun and possibly without shadow during parking, which accounts for 90% of the time. The tilt angle of the third panel on the right-hand side is adjustable: it can be directed towards the sun while parking at approximately 25°. By optimising solar energy gain, the tricycle is "sunbathing", which increases the charging power by up to 70%, similar to a fast charger. The top surface should handle about 70% of solar energy production for family tricycles, as windows require additional surface area.

The performance of the vehicle is moderate, but it should not be underestimated, because the same number of solar panels with better orientation and tilt angle on the roof can supply an energy-saving household. The authors state that solar energy is sufficient for individual passenger and cargo transport in Hungary. Solar operation can be scaled up: partial onboard solar production or 100% onboard solar energy, supplemented with 5 VDC or 12 VDC output or even a solar inverter for onboard solar energy output.

ECONOMIC CONSIDERATIONS

To develop a commercial solar vehicle, the base vehicle should be an existing, functioning, tested, legal, marketable, inexpensive and affordable model—in this case, an electric cargo tricycle. The manufacturer must fulfil international requirements and be registered for export, offering available spare parts and accessories, as the authors are not producers but an energy engineer and a physicist at Hungary's Edutus University. Unfortunately, closed-cabin cargo electric tricycles with 1,500 W motor power are not produced in Europe. Therefore, one of the manufacturers from China was selected [[27]]. According to material safety data sheets, a local distributor was preferred since batteries are hazardous products.

USABILITY, FUNCTIONS AND ERGONOMIC CONSIDERATIONS

Regarding usability, functions, and ergonomics, a closed and lockable cab and cargo compartment are preferred, considering weather conditions, user habits, comfort, and safety. The sitting position for the driver is mandatory, but there is no need—and no surplus energy—for heating, and cooling functions operate through natural and small-scale ventilation. This setup is expected to be more comfortable than an open motorcycle or bicycle. The tyres are thicker and more robust, which is essential for carrying cargo. The superstructure of tricycles may be modified according to regulations. Solar vehicles should satisfy the sustainable component of present transportation needs, for example, reaching destinations far from railroads or carrying varied packages, including larger and heavier ones, but they are not designed for hundreds or thousands of kilometres in a single trip. Despite the cargo design, the cabin has enough space for one passenger or a bag. The speed is similar to that of electric bicycles, adequate for everyday usage. One solar cargo tricycle can serve 2–3 people on a weekly basis, especially if a monthly surplus of 3–4 kWh from the grid is allowed, which is approximately 50 kWh annually. A combination of solar vehicles and other low-consumption modes is practical. For example, walking and cycling for shorter distances are more flexible and healthy under typical conditions, while choosing trains for longer distances provides faster and more convenient trips without driving stress.

DEVELOPED SOLAR VEHICLE TECHNICAL PARAMETERS

Specialised Chinese electric cargo tricycles were selected and developed as solar vehicle prototypes. The first has a 1,000 W motor and the second a 1,500 W electric motor, consuming around 5 kWh/100 km, but powered by solar electricity produced onboard. A closed cab and cargo box are preferred in rainy or snowy conditions; the rearview camera is also useful. The tricycle has three wheels, drum brakes, springs, a closed cab with two doors, a 1,500-litre cargo box with a right-side door and backdoor, a cab with fan, windows, mirrors, lights, indicators, sound signals, horn, rearview camera, motorcycle-type steering wheel, three gears, hill-drive mode, reverse, blue colour, and a spare wheel. It is essential to measure speed and battery voltage—standard functions for any electric tricycle. For testing and development, all inputs and outputs were measured in the energy balance: currents and voltages from the solar energy production of three panels, and currents and voltages of the electric motor. SunSnail 2.0 also includes a grid charger.

Each tricycle was supplemented with three solar panels—altogether 700 to 1,000 W_peak—each sized 1 m × 1.6 m; the tilt angle of the right-side panel is adjustable. They operate with three 300 W_peak solar charge controllers. Battery capacity is 60 VDC, 100 Ah, providing approximately 3–4 kWh, and two 48 V battery equalisers protect them from imbalance.

Speed is planned to be 20–25 km/h. The second vehicle has a stronger motor and can reach around 30 km/h on level ground, but according to Hungarian law, two categories exist: tricycles up to 45 km/h or up to 25 km/h. As it is not realistic for cargo tricycles carrying solar panels to travel at 45 km/h, the speed of the solar cargo tricycle is limited to 25 km/h.

The total weight consists of a 250 kg cargo tricycle (self-weight without batteries), 100 kg of AGM batteries—lithium-ion or $LiFePO_4$ equivalents would weigh half but cost twice as much—and 100 kg of solar panels with their supplements. As a result, functional cargo capacity is approximately 250 kg. Gas springs and strut bars assist in holding the adjustable solar panel in an optimal charging position while parked.

Sinus stand-alone inverters with 300 W were added this year, but any other 60 VDC to European 230 VAC sinusoidal inverter up to a maximum of 2,000 W can be used. It provides solar AC electricity independently from the grid wherever the solar tricycle operates or is parked.

The first solar cargo tricycle concept was designed for 100% onboard solar energy production. As described in the Results, it performs very well. Five years of operation prove that a 100% solar-powered cargo tricycle can meet most local transportation needs sustainably because it is lighter, slower, and smaller than a car, allowing daily solar energy to cover its energy demand. The second solar cargo tricycle includes a built-in charger with a 400 W grid-charging option and is expected to operate with over 80% onboard solar energy annually. A solar electric passenger tricycle was also designed in 2023 with one adjustable, more robust, longer solar panel on the roof and additional small side panels if necessary.

IMPLEMENTATION OF THE SOLAR CARGO TRICYCLE CONCEPT

In 2017, development began with a customised Chinese electric cargo tricycle in response to certain requests from the European market. It has a cargo door at the rear and can be covered with 5 m² of solar panels. Re-used panels were preferred because of cost reduction and preparation for high mechanical stress while driving. In 2018, an onboard computer was developed in cooperation with the Savaria Campus of ELTE University in Hungary. The data recorded by this device assists operation and provides the basis for analysis and evaluation. The onboard computer summarises the data from the three solar panels and the battery charge status every minute (Fig. 3). In 2019, the data acquisition system was further improved to increase measurement resolution and reliability. This modification enabled better planning of routes and higher utilisation of solar energy.

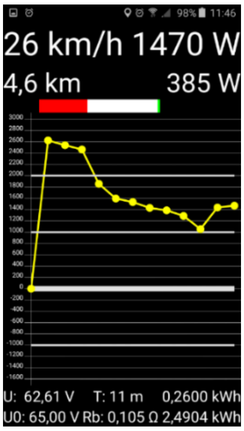

Figure 3. Details shown on the onboard application (speed, battery voltage, trip, motor performance, production of solar panels)

The developed application running on a smartphone shows the monitored parameters of the vehicle through an integrated Wi-Fi (wireless networking) connection. It also logs the coordinates and speed every 2–3 seconds using GPS (Global Positioning System) information. Since 2020, new types of solar panels have been tested. In 2021, new batteries were installed in SunSnail 1.0 after the first four years of usage.

In 2022, the data acquisition system was further improved for the second prototype with new parameters and measurement channels, as it has 230 VAC output and an option for grid charging. The second prototype—also based on a certified electric tricycle without energy supply and batteries—was developed and completed with solar energy technology by a project team of mechatronics engineering and technical management students in a talent care programme subsidised by the Ministry for Human Resources at Edutus University. SunSnail 1.0 and 2.0 operate with the predicted parameters detailed in Design, sizing and Technical parameters (3.2 and 3.3).

Figure 4: Checking batteries and battery equalisers

During the development of the vehicle (Fig. 4), several modifications were applied: a validated speedometer, larger mirrors, a solar-holder structure, gas springs and bars for the right-panel lifting option. The testing phase consisted of the following: selection and testing of batteries, optimal placement, cabling and testing of battery equalisers and solar charge controllers while considering the lifting function of the cargo box, developing the data acquisition and monitoring system, and calibrating and testing new parts and devices. Functional and informative decorations were also designed and fitted.

The budget remained below 1 million HUF (Hungarian Forint) in 2017 and the project was completed within 1.5 months. In 2022, both the cost and time requirements increased significantly, ending at around 3 million HUF over five months. The pandemic, the Russian–Ukraine war, and the economic crisis contributed to the rising costs of imports, including shipping, exchange rates, customs clearance, and VAT (value-added tax).

RESULTS

As the main result, key operational parameters of the 100% solar cargo tricycle (SunSnail 1.0) are summarised in Table 1, based on the first five years of operation since 2017. The overall covered distance was 24,748.4 km with 1,686 kWh total energy consumption, according to the onboard measured data. The cost of SunSnail 1.0 was recovered within five years. The average trip distance was 24 km with an average speed of 22 km/h.

Table 1. Solar cargo tricycle: five-year table of 100% solar operation.

	1st Year	2nd Year	3rd Year	4th Year	5th Year	Total in 5 years
Overall trip distance [km]	4768	5012.9	5073.2	4311.3	5583	24748.4 km
Total onboard energy [kWh]	261.7	367	361	309	387	1686 kWh
Benefit [thousand HUF]	274	244	153	150	167	991 thousand HUF (returned)
Speed [km/h]	18	21	23	23	23	22 km/h
Maximum distance [km/day]	103	116.3	130	98.6	106.3	max. 130 km/day
Average trip distance [km/trip]	22.7	26.5	24.2	20.7	26.3	24.0 km/trip

Compared to the first two years, from the third year onwards, the data acquisition system was improved because of the development and implementation of the real-time application with the onboard computer, which provided a better view of the energy balance and enabled more precise planning. Unfortunately, more extended tours became infrequent in the third and fourth years of operation because of epidemic circumstances. The amount of available energy and endurance increased due to the more efficient roof panel installed in the third year. After four years, the batteries had to be replaced, and an onboard solar inverter was added to provide solar AC power on-site for other devices, e.g., laptops, electric bicycles, and cordless screwdrivers.

SunSnail can carry up to 300 kg of cargo, which is suitable for everyday transportation tasks such as shopping, transporting firewood and tools, planting trees, camping, and similar activities. It does not consume fossil fuel, emit carbon dioxide, or pollute the air. As SunSnail 1.0 was never charged from the power grid, even Hungarian power plants did not emit pollution or produce nuclear waste because of this vehicle.

Datasets of daily distances and onboard solar energy were also collected during the five years (Figure 5). Some reduced but significant seasonality in usage can be observed. Solar power is partly stored in batteries; therefore, the vehicle can run in rain, snow, or at night, with speed depending on road and visibility conditions.

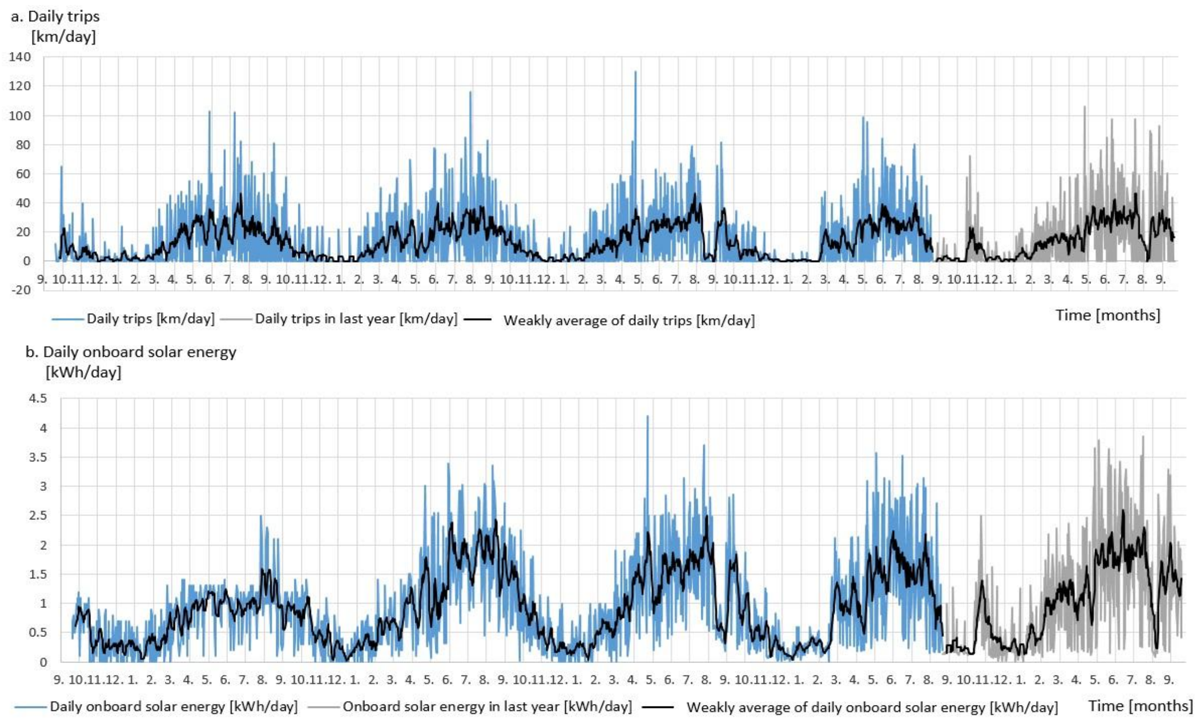

Figure 5. Daily trips [km/day] b. Daily 100% onboard solar energy [kWh/day] in five years

The performance of the vehicle is a few hundred watts during daylight hours, and the average is 175 W, which is consistent with the power of the solar panels and batteries. This means 295 to 388 kWh per year drives the vehicle, and 25% bypasses the batteries while operating.

The designed speed is 25 km/h, and during daily trips, it can maintain this speed for several hours. Normal endurance is 50–60 km on batteries in summer, whereas it can reach up to 100 km if the solar panels provide additional energy on a sunny day. It can "sunbathe" for one or two hours during stops. The longest distance in one day was 130 km.

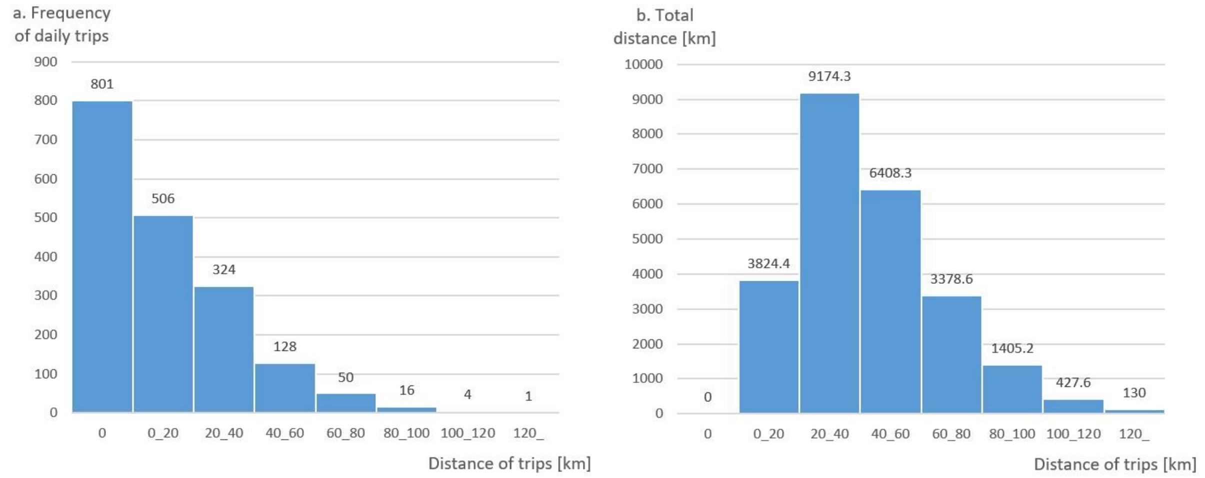

Figure 6. Histogram of daily trips b. Total distance of trips for 100% solar cargo tricycle

Despite the fact that the number of shorter trips exceeds 500, they cover only 3,824.4 km. Trips between 20 and 40 km amount to 9,174.3 km, and the remaining trips over 40 km represent more than 11,000 km of the 25,000 km travelled in five years (Figure 6).

The second prototype has run approximately 4,000 km in the first year. Compared to the 100% onboard solar SunSnail 1.0, it covered less distance in the early summer period and more in November–December, with approximately fifteen 2 kWh charges from grid-connected household solar systems. It works according to expectations, but trips are mainly short distances around the university.

The daily 100% solar energy balance in the strip diagram (Figure 7) shows three lines: onboard solar charging, consumption, and maximum energy potential for trips. The curve, with a standard deviation of 1 kWh, remains within a 3 kWh band, and the line is horizontal when the vehicle is stationary.

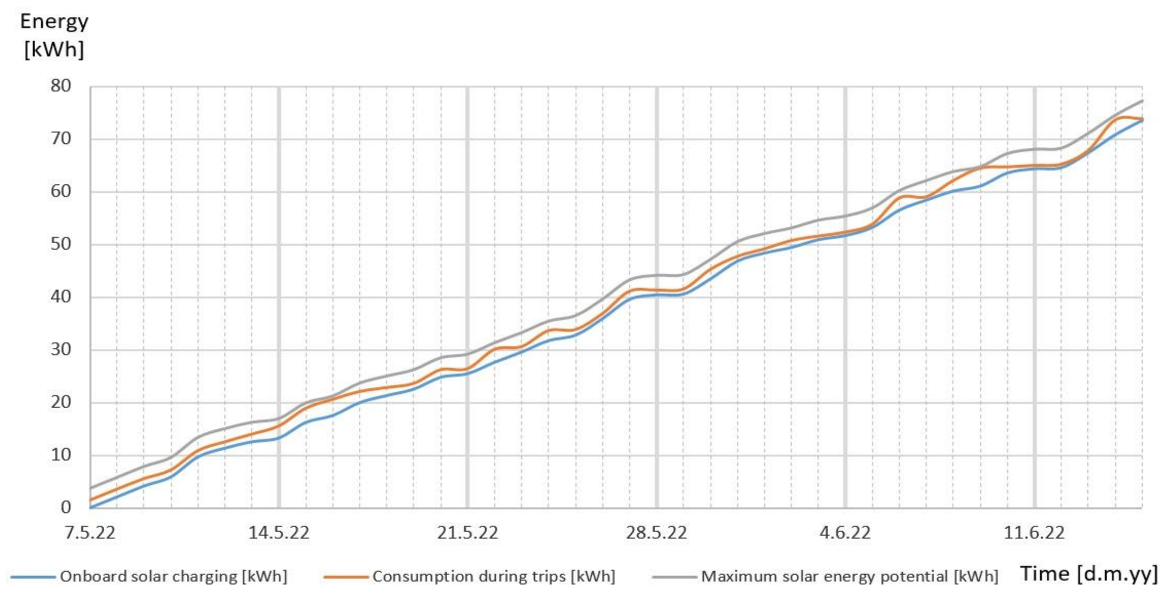

Figure 7. Strip diagram for 100% solar cargo tricycle: onboard solar charging, consumption and maximum energy potential for trips [kWh]

An advantageous combination of vehicles with small consumption and solar energy supply (Figure 8) was tested in late autumn. A one-day trip of 70 km from 9:45 to 13:20 was shared between two sustainable vehicles. More than half of the distance (20 km) was covered by the solar cargo tricycle, then the remaining segment (15 km) to the final destination and back was completed with an electric bicycle with a trailer. It provided healthy exercise for the driver while the solar vehicle was charging in the most optimal solar panel configuration. Finally, the solar cargo tricycle was used again from the parking location back home, with the electric bicycle and trailer placed in the cargo box. During the two hours of solar parking at noon, SunSnail collected 0.658 kWh of solar energy instead of losing 1.5–2 kWh with extra consumption. This is a significant difference, especially when managing a 3 kWh battery capacity in November.

Figure 8. Combination of solar cargo tricycle and electric bicycle and trailer on 7 November 2021, from Egyházasfalu, Hungary to Marienhof/Deutschkreuz, Austria and return

As a result, the effect of the combination (Figure 9) shows how both vehicles and the batteries are optimised for 100% solar energy use—in this example: 40 solar km in one day. The voltage of the batteries was kept at approximately the same level in the evening as in the morning (blue curve). It does not drop excessively in the evening, as it would without this technique (yellow curve). In the first five years, the battery voltage was continuously supervised: the maximum voltage drop was −8.1 V at 130 km, and the maximum charging was +5.9 V on 8 August 2018.

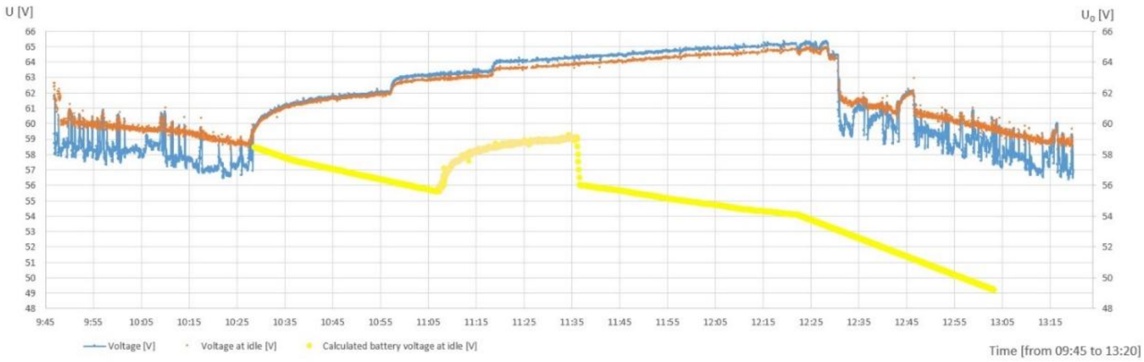

Figure 9. Effect of solar cargo tricycle and electric bicycle and trailer combination on battery voltage on 7 November 2021

According to their main specifications, the 100% solar cargo tricycle was also compared to an average fossil fuel car (Table 2). Important multiplier factors were calculated to emphasise the magnitude of differences in consumption and similarities in performance.

Table 2.100% solar cargo tricycle compared to a typical fossil fuel car.

	SunSnail, the 100% solar cargo tricycle prototype	Typical fossil fuel car in Hungary	Multiplier factor
Power density while refuelling	200 W/3 m^2	20 MW/3 cm^2	Car: 10^9 (1 billion)
Motor power	1.5 kW	150 kW	Car: 100
Stored energy	4 kWh	600 kWh	Car: 150
Weight	400 kg	1600 kg	Car: 4
Distance from next fuel station	min. 25000 km	1000 km	SunSnail wins: 25
Maximum daily distance	130 km	1300 km	Car: 10
Average speed	25 km/h	50 km/h	Car: 2
Cargo space volume	1.5 m^3	0.5 m^3	SunSnail wins: 3
Load carrying capacity	200 kg	400 kg	Car: 2
Fuel renewal time	1:1	1:5000000	Car: 5 million (not renewable)
Cost unit per km	26 HUF/km	100 HUF/km	Car: 4
Cost	1 million HUF	10 million HUF	Car: 10
Heating	0 kW	1.5 kW	SunSnail: it runs with 1.5 kW

DISCUSSIONS

According to the results and experience from five years of usage, the statement is confirmed: the Sun provides enough energy for daily passenger and cargo transport with fully onboard-generated solar power, even in Hungary and Central Europe, provided that a lighter, slower, and solar-powered electric vehicle such as a tricycle is chosen and developed instead of cars with high energy consumption. Apart from reaching high speed and distant destinations in a short time—beyond renewable energy capability—the vehicle functions similarly to automobiles, or even better, as it is capable of autonomous solar recharge. The calculated multiplier factors demonstrate the ecological, economic, and functional advantages of the 100% solar cargo tricycle design. An advantageous combination of this solar vehicle and other energy-saving mobility methods was also described.

CONCLUSIONS

This article aimed to draw attention to this new solar-powered, autonomous transportation method and to confirm the statements about sustainability and solar mobility discussed in Results (4) and Discussions (5). The study will continue with additional detailed analyses, and further developments are ongoing to improve solar electric tricycles for commercial use.

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DATA AVAILABILITY

Datasets related to this article can be found at https://doi.org/10.17632/8c5jpy3w7x.1, an open-source online data repository hosted at Mendeley Data.

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