Mathematical analysis of a self-service car wash in the aspect of application of renewable energy sources

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Abstract. The paper presents a model of a self-service car wash. Sub-models of water, electricity and natural gas consumption were developed. Heated water is used to wash vehicles and in winter to heat the floor. Electricity is mainly used to power high pressure pumps. The data to develop submodels were based on a time series of 1 year from a 5-station car wash located in central Poland. Chemical consumption and costs were not analyzed in this paper. Generally, this data is quite difficult to access and not provided by car wash manufacturers or owners. The developed model allowed estimating the possibility of using renewable energy sources in the form of solar collectors and photovoltaic panels to balance the energy demand of a car wash depending on the number of washing stands and car wash load. Application of solar collectors allows saving 334 m³ of natural gas per year and 11.2 MWh of electricity in the case of applying photovoltaic panels. The amount of electricity consumed by the carwash is so large that mounting the panels on the whole available area will not provide the required amount anyway. Installation of photovoltaic installation on the premises of touchless car wash is justified in the case of connecting the installation to the public network, which was treated as a battery. The cost of maintaining such a battery is 20% of each stored kWh. As a result of the applied solutions, the CO₂ emission will be reduced.

1. Introduction
The growing number of motor vehicles registered in Poland year after year results in an increased demand for the car transport infrastructure. According to the 2018 Statistics Poland report, the number of passenger cars in Poland was over 22.5 million. In 2019, more than 0.5 million new passenger cars were registered and this value increases by 15% every year [1]. This means that there will be a steady increase in the number of vehicles and a corresponding growth in the car wash market in the coming years. Regular car washing is one of the basic maintenance activities for every vehicle user. As reported International Carwash Association (ICA), on average, users wash their car about 10 times a year, in total amounting to about 270 million washes. In addition, according to the introduced regulations (on maintaining cleanliness and order in municipalities), it is prohibited to wash cars in residential areas and even on private properties [2].

International Car Wash Association distinguishes three main types of car washes:
1. automatic stationary car washes,
2. portal automatic car washes with a sliding rail,
3. self-service car washes.
In the whole Europe, about 64% of vehicle owners prefer to use self-service car washes and 6% manual car washes, and the remaining 30% use automatic car washes. There are about 11 thousand self-service car washes in Europe [3]. In 2010, there was about 11 thousand inhabitants per one car wash in Poland. In contrast, on developed markets, a single car wash serviced 4 - 5 thousand citizens. At that time, there were about 3.5 thousand car washes in Poland. The dominant trend among both drivers and entrepreneurs, according to the Polish Automotive Industry Association, is the use of self-service car washes. In 2019, about 300 car washes were sold, more than 10% more than the year before. On the Polish market, over 50% are self-service car washes. This proves the fact that cheap-to-operate solutions are popular [4].

Self-service car washes are preferred by the majority of customers due to their low cost of service, high availability in Poland, short waiting time in a queue and reduced the possibility of damaging paintwork compared to automatic car washes. Self-service car washes provide a similar final effect at a lower cost than that required when using an automatic car wash. Self-service car washes were created mainly for the people who want to wash their car quickly without waiting in a long line, spending at the same time much less money than in automatic car washes. According to the International Association of Automobile Manufacturers, self-service car washes use the least amount of water - about 68 dm$^3$ per washing cycle - this is an average value and it depends mainly on washing time, program selection and breaks between programs. This value at continuous work may be even 110 dm$^3$. A large part of the water consumption is related to the production of osmotic water used for rinsing, while electricity consumption can vary from 0.8 to 2.5 kWh. At the same time, 4, 6 or even 8 cars may be washed, in about 10 minutes, if the car wash is equipped with a sufficient number of washing stands. Manufacturers of stationary washers offer a maximum of 12 stations (for example Ehrle). This is due to the limitation of water volume flow rate at the water supply and sewage system connection. An additional limitation is the cost of purchasing a land plot for a car wash.

On the other hand, in manual car washes, the washing process lasts 20-30 minutes and usually only one stand is available. Manual car washes is carried out on the vehicle owner's own property or in specialized companies by their employees. The data comes from marketing statistics from the ICA and authors’ own observations and statistics. The washing process is more precise than in other car washes. In automatic ones, on the other hand, the cost is twice as high.

The washing process also involves significant energy consumption. Cold water alone is no longer used to wash cars, as it increases the water and detergent consumption. The optimal solution is to heat water to 60°C. Such temperature allows for the lowest water and detergent consumption and does not damage the car body [5].

Soft water obtained in the reverse osmosis process is used for rinsing vehicles. Reverse osmosis (RO) is a well-known and recognized application for desalination and drinking water production. It is the leakiest membrane and because of this it can remove a whole range of materials and compounds such as metal ions, monovalent ions (e.g. K, Na), acids, synthetic organic chemicals, emerging fouling, water salts, and dissolved and suspended materials. It was the first commercial membrane to be widely used, and over the past 40 years, the RO systems have greatly improved their energy efficiency [5]. The process produces very high quality water with only a few volatile organic compounds. However, it also requires a relatively high energy demand, because it needs a water pressure that is higher than the normal distribution pressure to pass the water to be treated through the semi-permeable membrane. Additionally, it has a significant waste stream. This reject stream is produced during membrane cleaning and flushing. The volume of the reject stream can reach 30% of the total volume of water to be treated [6].

Many car wash owners realize that a lot of water and energy is required to run their daily operations. For this reason, they are upgrading their facilities to accommodate more energy-efficient equipment and processes. As a result, they do not have to charge as much for their services because their energy bills remain low and accessible (over time). In the paper, the development trends of car washes were presented. They are mainly related to touchless car washing and water saving systems [7]. Replacing inefficient incandescent bulbs with LED bulbs helps to significantly reduce the electricity costs. The
lights in a car wash stay on all day, even when the machines are not running. Therefore, more energy-efficient bulbs help reduce both costs and energy consumption. Current carwash solutions use single or two-speed pump drives. Multi-speed drives (controlling the speed of electric motors with inverters) reduce the amount of energy or power consumed in the wash process. Not all washing programs require high pressure [8].

Renewable energy sources in the form of solar collectors to support the heating of process water allow reducing gas consumption and thus the CO₂ emissions [9]. In Poland, the annual total irradiation, on average, is 990 kWh/m². The average value of annual irradiation is from 950 kWh/m² (south-western part of Poland - Sudety area) to 1081 kWh/m² (eastern part of Poland). Diffuse radiation in Poland is on average 50%, in June 44% and in December 72%. The average annual insolation is 1600 hours, which is about 18.2% of the whole year, when it is possible to use solar radiation for solar energy purposes. However, it is worth noting that 75% of this time falls in the summer half-year, from April to the end of September, averaging 1200 hours. In the winter semester, from October to March, the value of solar radiation is three times lower, averaging 400 hours [10] [11].

Geothermal heating can also be used as an alternative heat source that is extracted from the ground around the facility. In this, the use of a heat exchanger along with a heat pump improves the heat balance of the car wash [12]. The use of reclaimed and preheated water for washing will reduce the thermal energy requirement. The installed wind turbine at the car wash site is an additional source of free electricity.

According to Kantar Millward Brown research conducted on behalf of WWF Poland Foundation in late 2018 and early 2019, almost 60% of Polish women and men perceived climate change as a real threat to themselves and their loved ones. More and more products are advertised as "organic", "ecological", "bio", "environmentally friendly", etc. and this is reflected in their increased sales.

There is a lack of the modeling studies focusing on individual carwash components as well as water recovery and treatment systems [13]. Additionally, the operation of the car wash control systems is modeled [14]. In the paper, the authors [15] describe the development of a new design for a roll-off washer designed to minimize manufacturing complexity, reduce weight and size, as well as improve the transportation and installation strategies.

The authors of this paper developed a simulation model of the car circuit mapping, nozzle adjustment based on the car circuit mapping, and the washing process using an automatic touchless car wash in the fusion360 software, and then developed a small scale hardware prototype [16]. The automotive aftermarket, which includes service, car washes, car care, insurance and auto finance, accounts for as much as 60% of the total automotive market. Car wash is the most common of these services, attracting online businesses. In paper [17], the authors proposed a concept based on the Internet of Things for automatic car wash mode and explained its development. In the paper [18], service time cost, service efficiency cost, service processing rate and customer arrival rate were used as decision variables to create a decision model for service pricing in the car wash industry.

2. Carwash model

The mathematical model of a touchless car wash consists of submodels of water, electricity and gas consumption, the amount of wastewater discharged into the wastewater system, and the amount of water dispersed into the environment. Chemical consumption and costs were not analyzed in this paper. Generally, this data is quite difficult to access and not provided by car wash manufacturers or owners.

2.1. Thermal energy consumption submodel

For the washing program, the water is heated to 70°C. Using water at 12°C, this requires an energy input of 73 kWh/m³. The anti-freeze system uses a continuous closed loop water circuit for the hose and lance system and heating pipes located in the reinforced concrete floor slab.

Figure 1 presents a submodel of gas consumption in a self-service car wash. During the car wash operation, the chemical energy stored in natural gas is used to heat up water for individual washing cycles and for the antifreeze system (floor heating by means of a coil filled with glycol). The generated
thermal energy not directly connected with the washing cycle is used for heating the floor, water in the
gun in winter time and dissipated to the environment (efficiency of the furnace and heating of the control
room box).

![Figure 1. A submodel of gas consumption in a self-service car wash.](image)

The maximum volume of gas flow rate during a complete vehicle wash program can be written with
a mathematical equation that is based on the average percentage of time spent in each program and
considering the amount of energy per hour for each program.

\[ V_{gas} = V_1 + V_2 + V_{other} \]  

where:

- \( V_{gas} \) – volume of gas used to wash the vehicle over a full wash cycle \([\text{m}^3]\)
- \( V_1 \) – gas consumption per cleaning program \([\text{m}^3]\)
- \( V_{other} \) – the amount of gas consumed by the antifreeze system and dispersed in the environment \([\text{m}^3]\).

According to the presented gas consumption submodel and data from Table 1, its average hourly value
at continuous operation is 1.50 \( \text{m}^3/\text{h} \). This value was obtained by dividing the amount of gas consumed
annually (13149 \( \text{m}^3/\text{h} \)) by the number of days and 24 hours. Hourly gas consumption can be as high as
2.58 \( \text{m}^3/\text{h} \) in January (total 1919 \( \text{m}^3 \)), when the heat produced is used to heat the floor, the washing lance
and is dissipated into the environment.

The demand of a car wash for the energy obtained from the chemical energy of burnt gaseous fuel can
be expressed by the relation:

\[ E_{heat} = V_{gas} * k_k * \eta_h \]  

where:

- \( E_{heat} \) – Energy demand [kWh]
- \( k_k \) – conversion factor
- \( \eta_h \) – efficiency of the gas boiler

The conversion factor is used to convert the volume units of consumed gas \( (\text{m}^3) \) into energy units
given in kWh (kilowatt hours), which represent the real heat of combustion of gas given by the
Distribution System Operator for the geographical area appropriate for the given gas consumption point.
It is calculated as the arithmetic mean of the heat of combustion from the months of the billing period
divided by 3.6. The heat of combustion is the amount of energy released when burning gas in such a
way that the water vapor contained in the flue gases completely condenses and the products of
combustion are cooled to their initial temperature [19]. The heat of combustion is always greater than
the calorific value. In the case of cold, high-methane gas type E, the standards state a minimum calorific value of 31 MJ/m$^3$ and a minimum combustion heat of 38 MJ/m$^3$.

The changes were forced by the European Union (Regulation (EC) No 715/2009 of the European Parliament and of the Council of 13 July 2009 on conditions for access to the natural gas transmission networks), which intends to unify the gas market in the Community countries. The reason is that in the EU countries, natural gas is supplied from various sources and imported from various suppliers. All this causes that gas has diversified chemical composition, which leads to various misunderstandings. Moreover, in Poland the supplied gas is divided into two types: E and L. The energy value of each of those types may be different, and the settlement in m$^3$ does not show that at all. This problem is eliminated by accounting in energy units.

2.2. Electricity consumption submodel

During the carwash operation, electricity is used to drive the pumps for individual washing cycles and to prepare soft water in the reverse osmosis process. Additionally, it is used for the control system. The electric energy not directly connected with the washing cycle is used for lighting. Figure 2 shows a submodel of electricity consumption in a self-service car wash.

![Figure 2. A submodel of electricity consumption in a self-service car wash.](image)

The maximum continuous power consumption during a complete vehicle wash program can be written with a mathematical equation that is based on the average percentage of time each program is running and considering the amount of power per hour for each program.

$$E_{el} = E_0 + E_1 + E_3 + E_4 + E_5 - E_{serv}$$

where:

\(E_{el}\) – the amount of electricity used to wash the vehicle over a full wash cycle [kWh]

\(E_5\) – energy consumption per wash program

\(E_{serv}\) – the amount of electricity used to service the car wash
3. Solar energy applications

3.1. Solar collectors

The hot water is used for the washing programs and for heating the anti-icing system in the winter (heating the floor with a glycol-filled coil). Column B of Table 1 shows the furnace gas consumption for domestic hot water (DHW). The highest gas consumption occurs in the winter months and the lowest in the summer months. The water is heated to 75°C, then through a mixing valve its temperature is set at about 55°C and this is what is directed to the wash. In order to analyze the possibility of the application of solar collectors in a car wash, gas consumption was adopted and presented in energy units (column C), taking into account that each m$^3$ of gas, according to the values of coefficients determined by the gas supplier on the basis of measurements of the average calorific value of the gas supplied during the year, is 11.1 kWh. The energy of the burning fuel (gas) is transferred to the heated water in the gas furnace with an efficiency of 97%. Column D shows the amount of energy that is transferred in a given month to the water heated from about 10°C to 75°C. At the same time this is, the energy demand of a 5-stand car wash in hot water shown in the figure. The power and productivity of the solar collectors should be selected in such a way that the energy produced by them does not exceed the minimum demand (6.6 MWh) in the month of August (see table 1 – column B and figure 3 – energy demand for hot water preparation at a 5-stand carwash during the year).

Poland is classified as a moderate climate zone. It is located between 49 and 54.5 degrees north latitude. The potential average useful energy of solar radiation in Poland is about 1000 kWh/m$^2$/year. The climatic conditions of Poland allow effective use of installations for about 6 months. The sunshine duration (the total time during which the sun's rays fall directly on a particular place on the Earth's surface) is 1600 h, and the optimum angle of inclination of the collector plane to the horizontal is 40° - 45° towards the south. Figure 4 shows the energy balance of a car wash with 20 collectors and a Hewalex VF1000-2 heater of 1000 dm$^3$ capacity. During the year, the solar installation will ensure about 13% of energy demand for heating hot water, taking into account the variant of operation of the installation for

Table 1. Gas and energy consumption by month from a 5-stand carwash (source: own research).

|       | Gas consumption [m$^3$] | Energy from boiler [MWh] | Energy demand [MWh] |
|-------|-------------------------|--------------------------|---------------------|
| A     | B                       | C                        | D                   |
| January | 1919                   | 21.3                     | 20.7                |
| February | 1425                    | 15.8                     | 15.3                |
| March   | 1209                    | 13.4                     | 13.0                |
| April   | 1140                    | 12.7                     | 12.3                |
| May     | 980                     | 10.9                     | 10.6                |
| June    | 980                     | 10.9                     | 10.6                |
| July    | 857                     | 9.5                      | 9.2                 |
| August  | 605                     | 6.7                      | 6.5                 |
| September | 613                    | 6.8                      | 6.6                 |
| October | 839                     | 9.3                      | 9.0                 |
| November | 1251                   | 13.9                     | 13.5                |
| December | 1331                   | 14.8                     | 14.3                |
| Annual | 13149                   | 146.0                    | 141.6               |
heating water to 50°C. The figure shows the variant in which the water is heated only by solar collectors to about 35°C. The installation works more effectively with a small temperature difference and with a large water intake, this variant will be plausible. The losses connected with heat losses in the buffer tank and in the solar collector will be reduced.

![Graph showing energy demand for hot water preparation at a 5-stand carwash during the year.](image)

**Figure 3.** Energy demand for hot water preparation at a 5-stand carwash during the year (source: own research).

![Bar graph showing energy demand of the car wash and the amount of energy produced by 20 solar collectors in particular months of the year.](image)

**Figure 4.** Energy demand of the car wash and the amount of energy produced by 20 solar collectors in particular months of the year (source: own research).

### 3.2. Photovoltaic system

In order to analyze the possibility of using photovoltaic panels in the carwash, electricity consumption was assumed. The amount of electricity consumed by the car wash is so large that mounting the panels on the entire available area will not provide the required amount of energy anyway.

A 5-stand car wash with an available area of 157 m² (5 x 4.80 m x 5.90 m and 2.70 m x 5.90 m) was assumed for the analysis. Photovoltaic panels would be arranged horizontally on the roof of the washing stands and container. The total power of the photovoltaic installation will be 14.5 kWp.
All of the generated energy from the photovoltaic panels will not be consumed by electrical equipment installed at the car wash. It was assumed that 30% of the energy from PV panels will be used directly to power receivers on the premises of the car wash and 70% of the energy will be transferred to the public power grid. According to RES, it can be collected during the year in the ratio 1:0.8 (installation up to 10 kWp) and 1:0.7 (installation 10-40 kWp). According to the draft amendment to the RES Act, prosumers can also be entrepreneurs.

The figure 5 shows the electricity consumption during the year and the energy produced by the 14.5 kWp photovoltaic system for a 5-stand self-service car wash. The photovoltaic system produces 11.2 MWh of electricity during the year, supplementing the annual energy demand of the car wash reaching 28.2 MWh. About 39% of electrical energy comes from renewable sources. On average, the car wash uses 2.3 MWh of electricity during a month. During the winter months, the electricity consumption is the lowest. Due to the prevailing weather conditions, fewer vehicles are washed, but electricity consumption due to lighting is higher. Moreover, during this period, the share of energy produced from the Sun decreases and is on average less than 12%.

Figure 5. Annual electricity consumption and energy produced by a 14.5 kWp photovoltaic system (source: own analysis).

4. Summary
The amount of electricity consumed by the 5-stand carwash is so large that mounting the panels on the entire available area will not provide the required amount of energy anyway. The analyzed photovoltaic panel system with the power of 14.5 kW produces 11.2 MWh of electricity per year supplementing the energy demand of the car wash which is 28.2 MWh per year. About 39% of the electricity comes from renewable energy sources. To sum up, establishing a photovoltaic installation on the premises of touchless car wash is justified in the case of connecting the installation to the public network, which can be treated as a battery. It is also possible for entrepreneurs, after the amendment of the RES Act in 2019. The cost of maintaining such a battery is 20% from each kWh stored.

The estimated payback time is 12 years, which, with a panel life of 20-25 years, is half the life of the panel. The payback time can be attempted to be reduced by matching the power of the PV system to the electrical loads installed at the carwash site. In this way, the contribution of 0.3 of the energy used on an ongoing basis could be increased. However, this would require measurement and analysis of the daily electrical power consumption.

The analysis of the possibility of using a solar collector installation in a car wash presented above shows that the higher the power of the installed installation, the faster its return. During a year, the solar collector system will ensure about 13% of the energy demand for hot water heating, taking into account
the variant of system operation for heating water up to 50°C. The size of the installation is proportional to its purchase cost, which will be compensated by a quick return and use of savings. In each installation, a significant component of the cost was the hot water storage tank, which can enter the gas furnace installation. The calculations did not take into account the positive impact of the installation on the efficiency of the furnace heating the water to 50°C, which will only reheat the water by another 25°C and thus require less energy (the gas furnace works more efficiently with a small difference between the inlet and outlet water temperatures).

An important aspect of using Renewable Energy Sources in car washes is the marketing aspect and attracting more customers to energy saving devices.

Solar installations could be installed on the existing car washes. The design of a solar installation for a car wash requires a deeper analysis to allow for the most efficient use. In addition, an analysis of the location in which it operates (insolation and shading effects) is very important. To sum up, the period after which the solar installation pays for itself can be still shortened; however, it requires conducting measurements and analysis of the daily energy consumption.

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