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*Full Length Research Paper*

# Exergy consumption analysis of the transportation sector of Senegal

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**Exergy analysis has become widely recognized and adopted as a powerful tool for physical and engineering systems analysis. In this paper, it was applied to transportation modes. Transport is second after the residential sector in Senegal when it comes to energy consumption and relies on imported fossil fuels. In 2013, it consumed around 32 PJ which represented 30% of total energy consumed in the country. Exergy use dynamics shows that roadways dominate and have been experiencing an increase in exergy utilization since 2000. Air transport which played important role till 2006 has very little contribution in 2013. The mean weighted exergy efficiency is low, 13.74% that is, more than 80% of exergy used is lost. This low performance is partly due to poor infrastructure, old car fleet and low level of organization. Therefore, appropriate measures should be applied to modernize the transportation sector, and specifically reduce fossil fuels use.**

**Key words:** Transport sector, exergy utilization, exergy analysis, exergy efficiency, fossil fuels.

## INTRODUCTION

Transport is a critical component of the economy that assures the mobility of people and goods from one area to another. The infrastructure comprises roads, airports, seaports, etc. on which goods, people and equipment move. Equipment is set to allow the mobility by carrying a determined quantity of goods and a number of people. Transport is based on the use of energy or better said its conversion. Various types of energy fuels can thus be used and transformed by different kinds of machines. Machines and fuels have evolved along history. Nowadays, mankind has the possibility to choose among large set of equipment; automotive, train, plane, ferry, etc. Each of them uses specific types of fuels. In ancient times, only natural means of transport (walk, water, animal) were used, but this progressively changed, especially during the industrial revolution when steam engines where invented. Coal played an important role as it was considered the paramount fuel for ships and trains. It lost its prestigious role as the oil products became popular in newly designed motors, more adapted for road transport. However, their uses have brought serious damage to the environment, which includes pollution, drought, frequent typhoons, etc. Negative effects of fossil fuels and climate change are now pushing to a shift from traditional fossil fuels (gasoil, coal, gasoline) to cleaner and environmentally friendly fuels, such as electricity,

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biofuels and hydrogen in transport (Browne et al., 2012; Fayaz et al., 2012).

In Senegal for instance, and according to a previous study, transport accounts for more than 10% of the GDP (Gross domestic product) and consumes around 32 PJ which represent 30% of total final energy consumption (Tchanche and Diaw, 2017). It is a four-mode system that comprises roadways, seaways, airways and railways. They are all based on oil products; gasoil, gasoline and jet fuel. Roadways and highways dominate and accounts for large percentage in the mobility (Tchanche, 2017).

Large proportions of vehicles are second-hand imported mainly from Europe, while a small proportion is mounted locally. Around 600,000 vehicles made up the car national car fleet, 60% use gasoil, and the remainder gasoline. Maritime transport is developed on the Atlantic coast where ferries carry on regular base people between Dakar and The Casamance regions. Senegal hosts a dozen airports, distributed across the country. A new airport is located in Diamniadio, some 50 km from Dakar, and is designed to host at least 3 million passengers per year. The government recently decided to enhance national traffic by opening a new airline company, Air Senegal. Since the independence in 1963, railways have been progressively let apart as more roads were built in the country. This was also the consequence of social and economic transformation that took place in the past fifty years. The mainline Dakar – Bamako is in poor physical condition, as operators successively went bankrupt. In view of modernizing the rail infrastructure, a rehabilitation plan was set by the government and an electric railway called TER between Dakar and Diamniadio was inaugurated early this year.

In 2000s, the country faced a severe energy crisis as a result of high crude oil prices and the government decided to set an energy statistics office based in the Ministry of Energy. The office aims to collect and analyse data related to the energy sector for better planning and coherent policy. The energy system of the country despite the mass of available data already collected is still not well understood. In a recent study, an analysis was carried out, and the first results were extracted (Tchanche, 2018). Senegal's energy system relies heavily on biomass and fossil fuels. Biomass is used in residential sector for cooking activities, while fossil fuels are used mostly for transport and electricity generation. Another outcome was that the economy of the country is at risk due to fossil fuels imports. Senegalese have been enthusiastic as their country is poised to become in a near future an oil producing country as oil fields have been discovered and expected production could reduce imports and bring additional revenues to the State. The present study focuses on the transport sector, and the analysis is carried out from an energy viewpoint.

The novelty of the work resides in the approach that combines both energy and exergy flows. Energy analysis is based on the first law of thermodynamics, which is the principle of equivalence between different forms of energy. In view of better utilization of natural resources, many authors have recommended the exergy concept which integrates the interaction between systems and their environment (Vosough et al., 2011; Wall, 2011; Novak, 2017). Exergy is defined as the maximum work that can be extracted from a stream when it comes to equilibrium with the environment and this concept is based on the second law of the thermodynamics. Exergy analysis was applied to different types of systems; buildings (Xydis et al., 2009), renewable energy systems (Hepbasli, 2008; Wall, 2014), communications systems (Aleksic, 2013), heat engines and power plants (Tchanche et al., 2010; Marchionni et al., 2018), societies and states (Wall et al., 1994; Mosquim et al., 2018), etc. and proved to be a useful tool for decision making. It has been used recently for analysis of transport sectors for performance assessment (Jaber et al., 2008; Koroneos and Nanaki, 2008; Badmus et al., 2012; Mitra, 2014). The same approach has been applied here to determine the efficiency of the transportation systems in Senegal. The present study is structured into several sections; (1) methods where theoretical background of the work is introduced, (2) results which are subsequently analysed and discussed and (3) a conclusion given at the end.

## METHODS

### Energy and exergy of a fuel

A fuel is characterized by its lower heating value (LHV), which is the energy content. Take m as the mass of the fuel (in kg), the quantity of energy (En) it contains is given as:

$$E_{n,fuel} = m.LHV \tag{1}$$

The total energy used within the transportation sector is the sum of energy used in each mode by all engines. And therefore, it is given as:

$$E_n = \sum_i E_{n,i} \tag{2}$$

The exergy of a fuel (chemical exergy) is evaluated using the following equation:

$$E_{x,fuel} = m.\gamma_l.LHV \tag{3}$$

Where $\gamma_l$ stands for the exergy factor based on lower heating value (LHV). Table 1 gives LHV for various fuels.

The total exergy used within the transportation sector is the sum of exergy used in each mode by all engines. And therefore, it is given as:

$$E_x = \sum_i E_{x,fuel,i} \tag{4}$$

**Table 1.** Lower heating value (HLV) of fuels (25 °C, 1 atm).

| Fuel | LHV (MJ/kg) | Exergy factor, $\gamma_l$ |
|---|---|---|
| Gasoline | 44.300 | 1.07 |
| Fuel oil | 40.400 | 1.07 |
| Diesel oil | 43.000 | 1.07 |
| Kerosene | 44.100 | 1.07 |

Source: Badmus et al. (2012).

### Energy and exergy efficiencies

The energy efficiency of a heat engine is the ratio of the useful power ($W$) produced to total energy input. It can thus be defined as:

$$\eta = \frac{W}{E_{n,fuel}} \quad (5)$$

The mean weighted energy efficiency of the transportation sector is the sum of energy efficiency of each engine category multiplied by the fraction ($p_i$) of fuel energy consumed. Therefore, the mean weighted energy efficiency can be written as:

$$\eta_g = \sum_i \eta_{m,i} . p_i \quad (6)$$

The exergy efficiency is the ratio of exergy contained in useful products to the exergy contained in all input streams. Thus, it is defined as:

$$\psi = \frac{W}{E_{x,fuel}} = \frac{\eta}{\gamma_l} \quad (7)$$

The mean weighted exergy efficiency of the transportation sector is the sum of the exergy efficiency of each type of engine multiplied by the fraction of energy consumed.

$$\psi_g = \sum_k \psi_{m,k} . p_k = \sum_{i,k} \frac{\eta_{m,i}}{\gamma_{l,k}} . p_k \quad (8)$$

## RESULTS AND DISCUSSION

Data related to the transportation sector of Senegal were collected from the Ministry of Energy for the period 2000-2013 (MINEE, 2005; MEDER, 2006, 2014; MINE, 2007, 2013; MINCITAIE, 2010), and further analyzed from both energy and exergy viewpoints. Exergy consumption, energy and exergy efficiencies were determined. Motors used in the transport sector bear different efficiencies linked to their thermodynamic design and technology. Diesel engines are based on Diesel's cycle, gasoline engines operate on Beau de Rochas/Otto thermodynamic cycle, while propulsion systems used in aircrafts are based on Joule's cycle. Theoretical analyses give higher thermal efficiencies, close or above 50% for these cycles. However, practical design allows lower performance and manufacturers of internal combustion engines, give rated efficiency of 28% for diesel and gasoline engines, and 35% for gas turbines. Nevertheless, these values do not remain constant during their lifetime, and in operation, it is estimated that for a fleet of cars, 22% can be considered for road vehicles, 28% for aviation and 15% for marine engines. The above values were proposed by Reistad for the transportation sector of the USA (Dincer et al., 2004; Utlu and Hepbasli, 2006). In regard to the conditions surrounding transport sectors in developing countries, these values can be misleading. Badmus et al. (2012) mentioned it in their study and proposed to use 14.68% for roadways. Similar remarks can be drawn for other modes, but no alternative has been proposed. Therefore, for Senegal we will use 14.68% for road vehicles, 28% for airplanes and 15% for marine engines.

Exergy consumed in the transport sector shows irregular variation as can be seen in Figures 1 to 4. It is seen that exergy is consumed mostly on roads which at the same time show constant increase as shown in Figure 1. The constant increase is in line with the increase of the number of imported and registered vehicles in the country. This number as shown in a previous work is in constant increase (Tchanche, 2017). In the early 2000s, second hand vehicles could not be older than five years of age, but a new law was passed on in 2012 that sets a new limit at eight years. The import of second-hand vehicles has spurred in the country, as members of the Senegalese diaspora see automotive sales as lucrative business. Statistics on automotive sales also show that most vehicles sold are second-hand, and in poor conditions. These poor conditions mean high fuel consumption in comparison with a brand new car.

The air mode had important amount of exergy before 2006, but since 2007 the amount of exergy consumed has been drastically reduced as seen in Figure 2. A brief recall of the history of the Senegalese civil aviation is necessary to understand the dynamics in the exergy consumption. Air transportation by African airlines does not seem to be a good business, as many hurdles are present in the sector. Few airline companies however make the exception. By 1971, Senegal has interests in two companies, Air Afrique and Air Senegal. In 2002, Air Afrique went bankrupt as a consequence of a lack of

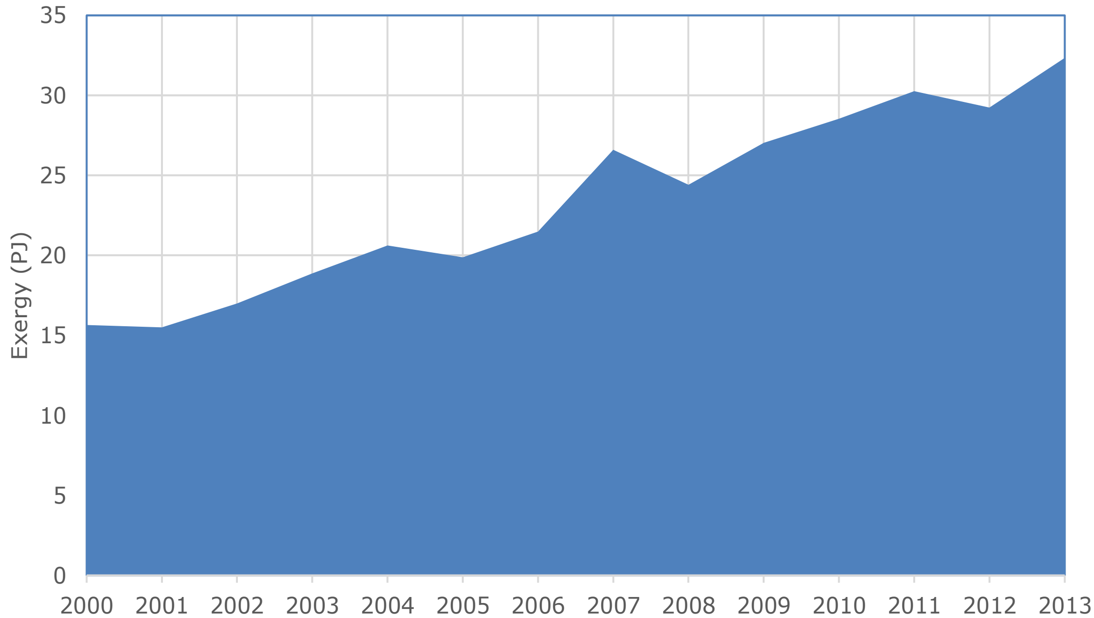


**Figure 1.** Exergy consumption dynamics on roadways.

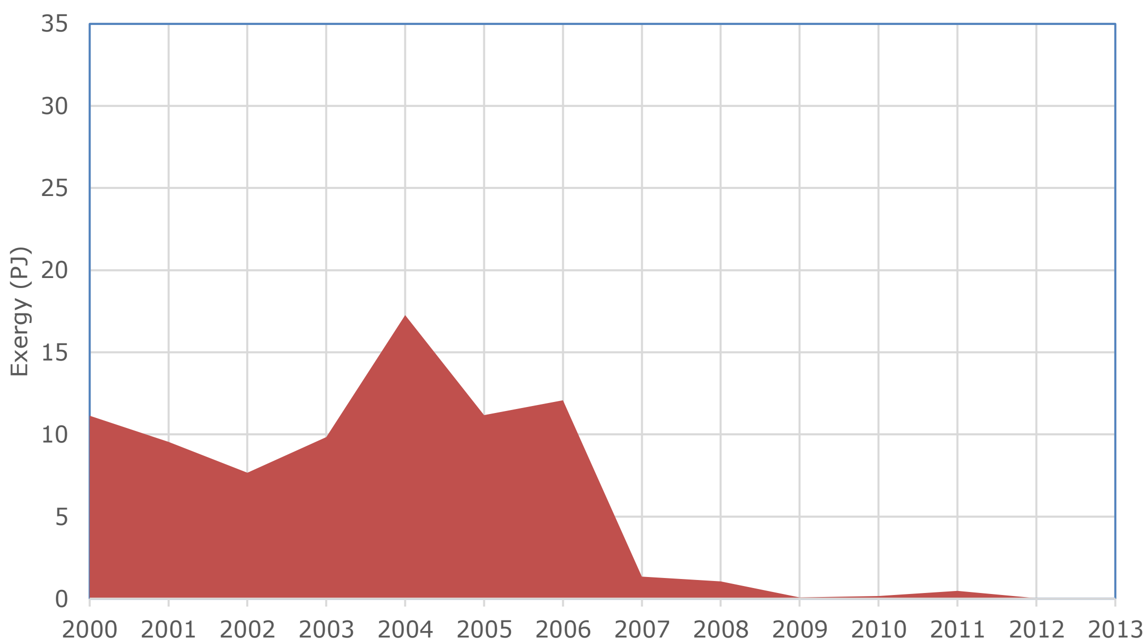


**Figure 2.** Exergy consumption dynamics in the aviation.

strategic management from member states that preferred their own national companies. Early in 2000, Air Senegal went bankrupt. The Senegalese government then decided to create a new company, called Air Senegal International (ASI). It started operating in 2001, but mismanagement and disagreements among partners didn't allow the company to live long, and then closed up in 2009. This explains why in Figure 4, from 2009 it does show very little or no exergy consumption. After the closure of ASI, some local businesses decided to team up with the government to found another company, Senegal Airlines, and its activities were launched in 2011. As you can see little exergy appears in 2011, but this other company went bankrupt and was dissolved in 2015. The amount of exergy consumed in the maritime subsector is relatively stable, around 1.4 PJ as can be

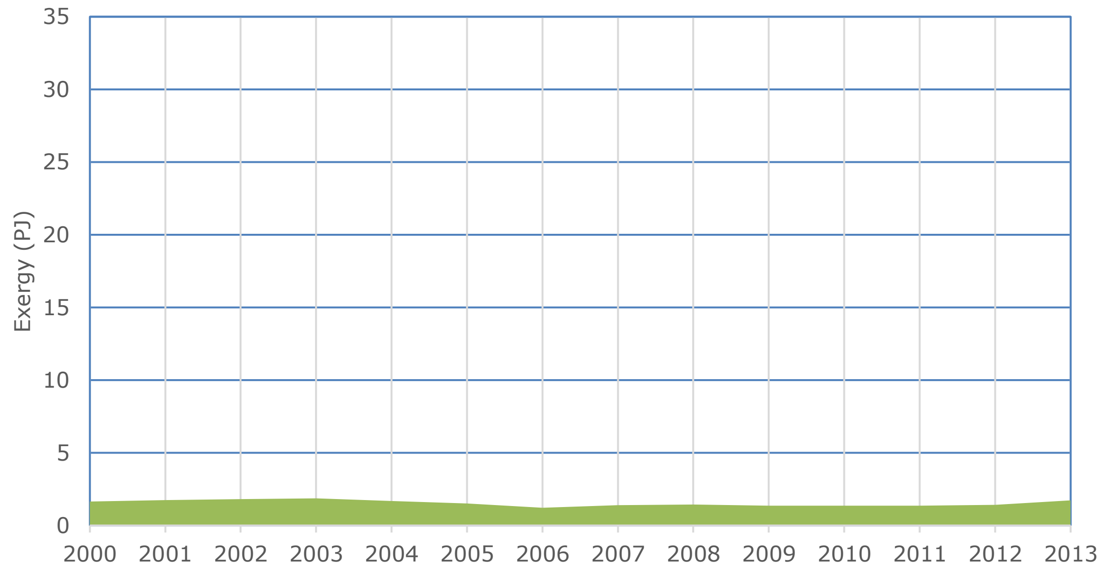


**Figure 3.** Exergy consumption dynamics on waterways.

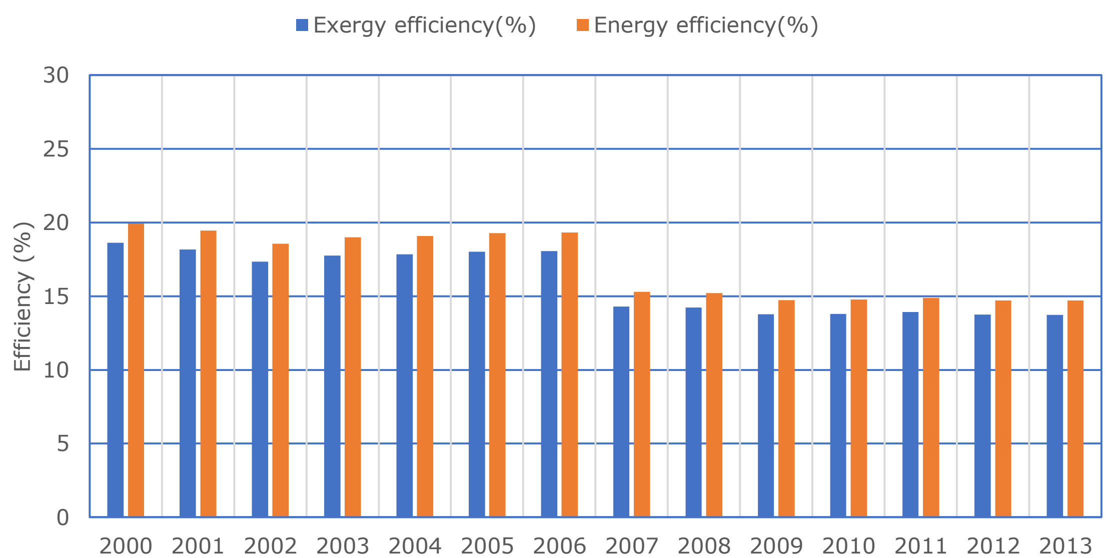


**Figure 4.** Mean weighted energy and exergy efficiency variation in the period 2000-2013**.**

seen in Figure 3. The exergy consumption here is due solely to ferries linking Casamance and Dakar regions and fishing activities. The traffic is not very important even though the number of passengers have been increasing. Political instability in the Casamance region and lack of investments in the maritime transport have prevented growth in this sector. It should be noted here that in the course of this study, railways were not taken into account due to lack of data. The amount of exergy displayed on different graphs is in line with the intensity of activities found within the transportation sector. It is here confirmed that road transport is the dominant mode and therefore have great impact on the development of the country.

Figure 4 shows the evolution of the energy/exergy efficiency of the whole transport sector. Energy efficiency is higher than exergy efficiency, but both decreased from 2006. Exergy efficiency shifts from its level of 18.62% down to 13.74% and energy efficiency from 19.92% down to 14.70%. The reduction in performance is due to low level of exergy consumed in the aviation mode – see exergy dynamics in the aviation on Figure 2. Results however, show poor performance of the transport sector and room for improvement. Excess exergy losses can be

**Table 2.** Exergy efficiency values in different countries.

| Country | Exergy efficiency (%) | Reference |
|---|---|---|
| Saudi Arabia (Ro+Ai+Wa)-2000 | 21.84 | Dincer et al. (2004) |
| Turkey (Ro+Ai+Ra+Wa)-2000 | 22.76 | Ediger and Çamdali (2007) |
| Senegal (Ro+Ai)-2013 | 13.74 | Present work |
| Jordan (Ro+Ai)-2006 | 22.70 | Jaber et al. (2008) |
| Greece (Ro+Ai+Ra+Wa)-2000 | 21.23 | Koroneos and Nanaki (2008) |
| China (Ro+Ai+Ra+Wa+Pi)-2008 | 20.41 | Zhang et al. (2011) |
| Nigeria (Ro+Ai+Ra+Wa)-2010 | 13.85 | Badmus et al. (2012) |

Ro: road, Ra: railways, Ai: air, Wa: waterways, Pi: pipes.

attributed to many reasons. The poor engines operation of old cars is one, as the average age of the car fleet is 20 years (Tchanche, 2017). Low efficiency means also mean waste of fuels and increased carbon dioxide and particles matter emission. Another reason worth mentioning is the poor quality of road infrastructure, most kilometres of roads being unpaved and paved, are in poor conditions due to lack of maintenance. Senegal is a net-oil importer country which imports crude oil to be refined locally, and oil products of poor quality. In this context, increasing the performance of the transport sector would mean a lot of financial resources saved. Another advantage associated to the reduction of fossil fuels consumption is the improvement of air quality and less cases of respiratory illnesses and diseases. Air pollution from traffic has become a major concern in Dakar where concentrations of pollutants are usually above acceptable levels set by the World Health Organization (Faye, 2012). Therefore, it is absolutely necessary to curb down the quantity of fossil fuels used in the transport sector while modernizing the transport sector.

Table 2 gives values of exergy efficiencies in many countries. Most values are above 20%, and Turkey has the highest exergy efficiency. Lowest efficiency values are found for Senegal and Nigeria. These values were calculated based on the same hypothesis for road transport as they show similarities. Hypothesis used by most authors are based on Reistad’s work (Utlu and Hepbasli, 2006), and could be misleading as values for engine’s efficiency vary from one country to another. A sound approach would consist of considering measured values from a car fleet, and apply statistical analysis to extract representative values. However, exergy performance of transport sector obtained is low. Close to 80% of exergy consumed is dumbed in the environment. This calls for a new thinking.

## Conclusion

Transport is an important component of the economy which assures the mobility of people and goods from one area to another, and requires a particular attention pertaining to its role. It becomes therefore a necessity to assess its performance using appropriate tools. In this study, exergy analysis was applied, and results show poor performance of the transport sector. It thus calls out for necessary improvements. For the specific case of Senegal, it is absolutely important that national car fleet be renewed and ways being sought to reduce the negative impacts of higher polluting diesel oil massively used on roads.

## CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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