Energy 168 (2019) 70–79

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Energy and emission impacts of liquid fueled engines compared to electric motors for small size motorcycles based on the Brazilian scenario

Natália de Assis Brasil Weber [a, *], Bárbara Pacheco da Rocha [a], Paulo Smith Schneider [a], Luiz Carlos Daemme [b], Renato de Arruda Penteado Neto [b]

[a] *Federal University of Rio Grande do Sul, Brazil*
[b] *Institutos LACTEC, Brazil*

A R T I C L E I N F O

Article history:
Received 30 April 2018
Received in revised form
23 October 2018
Accepted 15 November 2018
Available online 19 November 2018

Keywords:
Electric motorcycles
Ethanol fueled engines
Well-to-wheel approach
Primary energy factor
PEF
Brazilian energy matrix

A B S T R A C T

Real data from dynamometric essays of electric and internal combustion engines motorcycles pointed out a 3 times superior energy performance of electric driven vehicles (47.06% efficiency) compared to the average value for liquid fueled engines (15.32%). That conclusion motivated a more comprehensive assessment, based on a bottom-up methodology together with the Primary Energy Factor PEF, in order to enlarge the energy chain by considering the Brazilian energetic matrix. Environmental impact is considered through the evaluation of greenhouse gases. PEF is calculated for five motorcycles based on 2010 to 2016 production data, followed by a projection for the years 2021, 2025 and 2026. PEF average values for electric and liquid fueled motorcycles are 3.5 and 7.1 respectively. The experimental tank-to-wheel efficiency ratio of 3 to 1 from dynamometric essays turns to be a well-to-wheel 2 to 1 ratio whenever the enlarged energy chain is considered. PEF method applied to dynamometric results shows that electric driven motorcycles are still more energy efficient than liquid fueled similar vehicles for the Brazilian matrix. Emissions from electric conversion are still less harmful, nevertheless battery impact must be better studied.

1. Introduction

Transportation is a major participant of the global primary energy, with an approximate share of 27% of energy demand [1] and greenhouse gas emissions, with more than 90% coming from gasoline and diesel [2]. Moreover, studies show that most of the growth (94%) in the transportation energy use occurs in developing countries [3]. Renewable sources are 43.2% of the Brazilian energy matrix [4], with a significant role of hydropower and ethanol. Transport sector is responsible for 32.5% of the country's energy consumption, with 44.0% from diesel, 29.4% from gasoline and 16.4% from ethanol.

Worldwide Electric Vehicles EV are gaining more attention especially due to its environmental friendly character. Despite the potentials and advantages of introducing electric transport in urban areas, Electric-Two-Wheelers E2W, such as e-bikes, e-scooters, and e-motorcycles are still untapped in Brazil. Weiss et al. [5] have shown that E2W vehicles are generally more energy-efficient, less polluting than conventionally-powered motor vehicles and also can reduce traffic noise and road congestion. They also pointed out some risks concerning environmental impact and the dependency on the profile of the electric grid and its driven forces, and suggested to perform case-specific assessments before drawing conclusions about their sustainability, as part of an integrated urban mobility planning.

Slow uptake of EVS are reported to be due to their limited driving range and the comparatively high prices, but policies, incentives, and the growth of charging infrastructure are helping to make these vehicles more viable for consumers [6]. Main obstacles for E2W market growth are strong demand for gasoline-powered motorcycles, bans on E2Ws due to safety concerns in urban areas, and growing support for public transit [7]. These authors concluded that improvements in E2W and battery technology, strong local regulatory support, flexible enforcement of E2W standards and deteriorating of public transit services could increase E2W

---

[*] Corresponding author.
E-mail address: weber.nati@gmail.com (N. de Assis Brasil Weber).

https://doi.org/10.1016/j.energy.2018.11.051
0360-5442/

Nomenclature

CH_4	Methane
CO	Carbon Monoxide
CO_2eq	Carbon dioxide equivalent
E100	Ethanol 100%
E22	Ethanol 22% blend
E61	Ethanol 61% blend
EE	Electric Motorcycle
EROI	Energy Return on Investment
$g\ km^{-1}$	Grams per kilometer
$GHG_{blend,prod}$	Greenhouse gases from liquid fuels production
GHG_g	Greenhouse gases from gasoline production
GHG_{eth}	Greenhouse gases from ethanol production
$GHG_{blend,use}$	Greenhouse gases from liquid fuels burning
$GHG_{elec,\ prod}$	Greenhouse gases from power generation plants
GHG_{source}	Greenhouse gases from each energy source
$GHG_{elec,\ use}$	Greenhouse gases from motorcycle use
kWh	Kilowatt Hour
kWh/km	Kilowatt Hour per kilometer
Mc	Internal Combustion Motorcycles
Mtoe	Million Tons of Oil Equivalent
MWh	Megawatt Hour
N_2O	Nitrous oxide
NOx	Nitrogen oxides
THC	Tetrahydrocannabinol
x_i	Energy Source
x_g	Gasoline ratio
x_{eth}	Ethanol ratio

Abbreviations

EV	Electric Vehicle
E2W	Electric Two-Wheeler
HEV	Hybrid Electric Vehicle
PEF	Primary Energy Factor
GHG	Green House Gas
LCA	Life-Cycle-Assessment
WTW	Well-To-Wheel
ICE	Internal Combustion Engine
PEC	Physical Energy Content Method
TCE	Technical Conversion Efficiencies Method
TTK	Tank-To-Wheel
NG	Natural Gas
LNG	Liquefied Natural Gas

Greek symbols

η_{elec}	Electricity generation efficiency
$\eta_{oil,ext}$	Extraction energy efficiency
$\eta_{oil,ref}$	Oil refining efficiency
η_{oil}	Gasoline production efficiency
η_{eth}	Ethanol production efficiency
η_{blend}	Fuel blend efficiency
$\eta_{,Mc}$	Overall motorcycle efficiency

penetration.

Market offers a wide option of electric driven motorcycles, ranging from small and simple models, sometimes similar to bicycles, up to sophisticated and powerful motorbikes, with outstanding performances and disruptive design concepts. Even considering distinct sizes and technologies, E2W displayed significant reductions in climate change contributions compared to ICE motorcycles, with similar total ownership costs per kilometer [8]. That behavior concern E2W charged with electricity from fossil fuels or not, and authors also pointed out that smaller motorcycles presented much better environmental performance than larger ones.

Technical development is on the run, and constructors already identified the worldwide tendency to go electric, but state policies must follow and support the accomplishment of this change and guarantee the consolidation of a new electric chain. India displayed more than 400,000 E2W in 2014, most of them (95%) low speed electric scooters that do not require registration and license, and a few thousand electric cars. The Indian Government launched the Faster Adoption and Manufacturing of Hybrid Electric Vehicles HEV and EV scheme to provide incentives for two and four-wheelers, expected to provide support over a two-year period [9].

Motorcycles have become a major source of urban air pollution in Taiwan, which led the government to implement carbon emission controls by stabilising energy performance and emission standards for motorcycles [10]. In addition, the government has launched measures such as: exemption of excise tax and fuel tax for electric motorcycles and price subsidy for buyers. Authors also reported that the benefits of the subsidy policy had a large and positive effect on the diffusion of electric motorcycles in Taiwan and have two folds: allowing consumers to receive positive investment benefits through the purchase of an alternative transportation mode, and to enhance production scale economy.

On the opposite way, Chinese authorities had signed out since 2011 that e-bikes were not welcome on urban environment but only light ones, powered by Li-Ion batteries [11]. Government claimed that E2W were not safe, contributed to traffic congestion and were not environmentally friendly as they carried lead acid batteries. The same author alerted to further social, economic and environmental impacts of that restriction, that can cause car sales to increase, followed by air pollution growth and a negative impact on everyday life of low-income population, that relayed on low quality public transport.

Since 2017, a national ecological bonus for low emission vehicles in France (Decree number 2016-1980) came into force to stimulate the purchase of two or three-wheel motor vehicles and electric motor quadricycles. The decree provides a 27% acquisition cost aid limited to € 1000 [12].

In Brazil, electric, hybrid or hydrogen-powered four-wheel vehicles benefit from a 35% import tax release since 2015 [13]. Unfortunately, alternative propulsion motorcycles were not included in this exemption, although motorcycles represent approximately 27% of the registered fleet of vehicles in 2017 [14]. Most of them are factory tuned to be fueled with a gasoline and ethanol mixture, called flexible or dual-fueled motors, capable to run with a minimum 25% addiction of ethanol to regular gasoline, which can go up to 100%.

Brazil benefits from a diversified renewable energy matrix, if compared to the global average, with a growing introduction of intermittent sources, as solar and wind power. The role of EV in the Brazilian fleet, and in particular E2W, led to perform dynamometric tests [15] with Brazilian market motorbikes fueled with different gasoline to ethanol mixtures and submitted to a standard traffic routine, in order to evaluated and assess their energy efficiency and pollutant emissions. The present paper is based on that report and extends the assessment by a proposed bottom-up method to take into account the energetic chain performance for electric and liquid fueled motorcycles, committed to greenhouse gas emission standards. It aims to identify the most suitable methodology for the Brazilian scenario, also adapted to other developing countries.

2. Methods for energy performance analysis

Top-down and bottom-up models [16–19] are two paradigms that reflect different approaches to analyze system energy flow. Top-down model starts from aggregate data and disaggregates them down as much as possible in an attempt to provide a comprehensive model, connecting production processes along with economic sectors. On the other hand, the bottom-up approach starts with highly disaggregated data and ends up aggregating as much as possible. Each of the production pathways are modeled as a series of technological processes which exchange mass and energy with each other and with the environment [20]. It can be said that while the first approach is rather built on an engineering philosophy, the later one tends to represent the view of economists [19]. Besides their particular strengths and weaknesses, model choice comes from the assessment priority point of view for a given system.

Top-down approach is commonly employed to compare and evaluate vehicles and motorcycles, such as Life-Cycle-Assessment LCA and Well-To-Wheel WTW [8,21,22]. LCA is characterized by covering the entire life cycle of a product, process or activity [23], and it is a product-oriented approach, based on estimated inventories and uniform conditions of processes. The LCA performed by the Asian Development Bank [22] for the Chinese market concluded that “E-bikes can provide very environmentally efficient transport for short distances to access transit stations. Depending on load factors, they can be much more environmentally friendly and cost-effective than feeder bus service and provide better service”.

In its turn, the WTW approach allows for assessing the impact of a given fuel by adopting specific energy pathways, based on sets of assumptions. It refers to the entire process of energy flow and its GHG emissions, from the mining of the energy source to the driven vehicle [24]. Differently from LCA, the preliminary and decommissioning phases are not counted in WTW analysis, considered as externalities [23].

The bottom-up approach allows modeling the impact of distinct, well defined technologies on the long-term development of energy consumption. It enables to assess the effects of technology-oriented policies, the evolution of the end-uses consumption, and their energy efficiencies over time. These capabilities led the bottom-up approach to be chosen in the present work to assess the energy efficiency of motorcycles driven by different fuels in the Brazilian context.

2.1. Analysis overview

Energy efficiency of motorcycles driven by different fuels was performed based on a bottom-up approach, by assessing efficiencies of direct transformations.

The Primary Energy Factor PEF was chosen as the efficiency parameter to compare motorcycle energy consumption. PEF estimates the amount of primary energy needed to satisfy the final demand, either electricity, gas, gasoline or heat [25]. PEFs are widely used by the European Union in legislation [25,26], standards [27], and scientific publications [28]. Its strength relies on the ability to describe complete energy systems, from generation to final consumption [28]. Its weaknesses are the factor variability according to the method, the chosen period, as well as the selection of system boundaries. Its accuracy depends on defining variables that reflect reality [26].

PEF aims to reduce primary energy consumption, by encouraging end-users to switch to energy carriers with lower conversion factors. Whenever the switch is made to fossil fuels, GHG emissions will increase simultaneously, and PEF must be followed by indicators as CO_2 emissions factor (CO_2eq/MWh), energy cost and radiative emission [26].

3. Methodology

A bottom-up approach based on the PEF was chosen to compare motorcycle efficiencies when fueled either by electricity or liquid fuels, willing to represent the country's energy system for a given period, as depicted in Fig. 1.

Assessment starts at Point 1, a common spot or border to all further energy paths, with data collected along the dynamometric essays reported by Daemme et al. [15]. The electricity, gasoline and ethanol paths are presented as follows:

- Electricity: Point ELEC-2 is the one used to calculate the E2W efficiency, and it was placed outside the motorcycle border, where the vehicle was charged. Electricity distribution and transmission efficiency throughout the electric network were estimated from points ELEC-2 to ELEC-3, followed by power generation through points ELEC-3 to ELEC-4, where the proposed energy chain ends up. Point ELEC-4 corresponds to the primary energy source conversion.
- Gasoline: Data collected at point GAS-2 allows for the calculation of the internal combustion motorcycle efficiency. The conversion of petroleum into gasoline and other products takes place at GAS-3, followed by oil extraction at GAS-4.
- Ethanol: Point ETH-2 also accounts for the motorcycle efficiency and point ETH- 3 for the losses related to all the processes involved in ethanol production.

3.1. Motorcycle efficiency

Indoor dynamometric tests reported by Daemme et al. [15] for four internal combustion (Mc#) and one electric (EE) motorcycles (Table 1) were taken as base data for the energy assessment proposed in the present work. All motorcycles were submitted to a common driving cycle routine and a simultaneous acquisition of flue gas emission.

Liquid fueled motorcycles Mc1 to Mc3 run on a blend of 78% gasoline to 22% anhydrous ethanol volume ratio, called E22. Mc4 was the only flex fuel engine, fed with different gasoline/ethanol blends: E22, E61 (50% E22 and 50% hydrous ethanol) and E100 (100% hydrous ethanol). The Mel motorcycle was equipped with four 12 V lead acid batteries, delivering 35 Ah at 48 V, and the engine develops 2 kW, with 50 km autonomy and 60 kmh^{-1} maximum speed.

Next section presents the methodology for efficiency calculation, applied to the three energy paths. They correspond to energy conversion processes that took place starting from point 2 in Fig. 1.

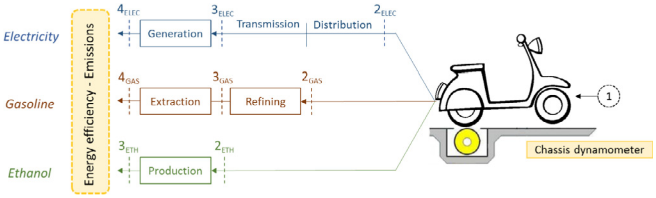

Fig. 1. Scheme for the PEF assessment of motorcycle efficiency fueled by electricity or liquid fuels.

Table 1
Technical details for Internal Combustion Engines (ICE) and Electric motorcycles.

Motorcycle	Emission regulation	Engine	Injection fuel system
Mc1	Euro I	ICE/125 cc	Carbureted
Mc2	Euro II	ICE/100Ccc	Carbureted
Mc3	Euro III	ICE/125 cc	EFI
Mc4	Euro III	IEC/150 cc	EFI/flex fuel
Mel	n/a	Electric/2 kW	n/a

EFI = Electronic Fuel Injection.

3.2. *Electrical grid efficiency*

Losses along the Brazilian electrical grid were reported by ANEEL [29] as 4.0% for energy transmission and 13.5% for distribution, corresponding to the path ELEC2 to 3 in Fig. 1.

Literature indicates five different approaches to calculate conversion efficiency of primary into secondary sources, which corresponds to the step ELEC-3 to 4 [25–27,30–32]. Their differences rely on how the conversion efficiency of primary energy sources are accounted from nuclear power and renewable energy (hydropower, solar power, geothermal power, etc.). Two distinct methods were applied in this study, as they can lead to a significant impact on the PEF estimation: The Physical Energy Content Method and the Technical Conversion Efficiencies Method [31].

The Physical Energy Content Method is based upon the definition that primary energy should be the first energy form downstream in the production process for which multiple energy uses are practical. Wind, solar photovoltaic and hydro sources, including storage, run-of-river, tide, wave and ocean, are primarily used for electricity conversion, and 100% efficiency is assumed. Biomass energy conversion can be directly accounted for by the product of input mass to heat value, although it can be used in multiple forms, like conversion to bio-fuels, food, and firewood. Therefore, even though biomass is a renewable source, in this method its conversion losses are considered.

The Technical Conversion Efficiencies Method considers primary energy to be the one that have not been subjected to any prior conversion. As a consequence, this method uses the technical conversion efficiency between energy source and generated electricity or heat, to calculate the primary energy demand per unit of energy generated [31].

Electric generation efficiency η_{elec} along the steps ELEC-3 to 4 is then calculated by Eq. (1)

$$\eta_{elec} = \sum x_i \eta_i \tag{1}$$

After possessing these data, a weighted sum is proposed to estimate the electricity generation efficiency η_{elec} between points 3 and 4, based on the ratio of the energy provided by each source x_i and its conversion efficiency η_i.

3.3. *Liquid fuel efficiency*

The energy conversion pathway for gasoline and sugarcane ethanol only concerns direct energy losses, disregarding their distribution.

Gasoline conversion chain starts with crude oil extraction and ends up with as a final product on refineries. Almost half of the Brazilian oil fields are placed off-shore in the pre-salt layer, with oil layers at 7 km depth, 2 km water layer and high CO_2 content [33], with important technical and operational challenges and high cost of production. The Energy Return on Investment (EROI) was chosen to estimate the gross amount of required energy to deliver one unit of the available energy [34]. Its classic definition is the ratio of the amount of usable exergy delivered from a particular energy resource to the amount of exergy used to obtain that energy resource, but also the gross amount of energy required to deliver one unit of the energy available. Therefore, the extraction energy efficiency $\eta_{oil,ext}$ is defined in the present paper by Eq. (2)

$$\eta_{oil,ext} = \frac{EROI - 1}{EROI} \tag{2}$$

Production data concerning gasoline refining are available in the annual IEA balance, allowing to calculate the oil refining efficiency $\eta_{oil,ref}$. Overall production efficiency for gasoline can be found according to Eq. (3)

$$\eta_{gas} = \eta_{oil,ext} \eta_{oil,ref} \tag{3}$$

Data for the amount of fossil energy invested to produce Brazilian sugarcane ethanol can be found in Refs. [35–39], as the ratio between the total energy contained in the biofuel to the total fossil energy invested throughout its production, including agricultural and industrial processes. That energy balance can be seen as an analogue number to the EROI and the production efficiency η_{eth} (Eq. (4)) can be used

$$\eta_{eth} = \frac{EROI - 1}{EROI} \tag{4}$$

Regular Brazilian gasoline is actually blended with sugarcane ethanol, starting with 22% on volume basis. A weighted average is proposed (Eq. (5)) to express the fuel efficiency η_{blend}.

$$\eta_{blend} = x_g \eta_{gas} + x_{eth} \eta_{eth} \tag{5}$$

with x_g and x_{eth} the ratio of gasoline an ethanol.

3.4. *Motorcycle energy efficiency*

The energy efficiency for each motorcycle tested under laboratory conditions was estimated according to the equations on Table 2, summarizing the energetic losses pointed in Fig. 1.

PEF for each of them can be calculated as the inverse of their correspondent energy efficiency.

3.5. *Emissions*

The evaluation of Greenhouse Gases GHG emissions gives a counterpoint to the PEF analysis, regarding an environmental perspective. Assessment concerned fuel production and its emissions after burned.

Greenhouse gases from liquid fuels production $GHG_{blend,prod}$ were calculated by a weighted average of individual emissions from gasoline and sugarcane ethanol as shown in the Eq. (11):

$$GHG_{blend,prod} = x_g GHG_g + x_{eth} GHG_{eth} \tag{11}$$

Table 2
Energy efficiency summary according to motorcycle type.

Motorcycle	Energy efficiency	Equation
Mc1	$\eta_{,Mc1} = \eta_{blend} \eta_{Mc1}$	6
Mc2	$\eta_{Mc2} = \eta_{blend} \eta_{Mc2}$	7
Mc3	$\eta_{Mc3} = \eta_{blend} \eta_{Mc3}$	8
Mc4	$\eta_{Mc4} = \eta_{blend} \eta_{Mc4}$	9
EE	$\eta_{EE} = \eta_{elec} \eta_{EE}$	10

The same procedure was employed to calculate greenhouse gases from liquid fuels burning along their use $GHG_{blend,use}$, with data collected at the exhaust of each motorcycle.

Emissions related to the power generation plants that compose the electric matrix $GHG_{elec,prod}$ were calculated from a ratio of emissions from each energy source, as shown in the Eq. (12):

$$GHG_{elec,prod} = \sum x_i GHG_{source\ i} \tag{12}$$

Emissions coming from motorcycle use were not accounted ($GHG_{elec,use} = 0$).

4. Case study: Brazil

PEF and GHG were calculated for the five motorcycles presented in Table 1, with energy data from 2010 to 2016, followed by a projection for the years 2021, 2025 and 2026.

4.1. Motorcycle efficiency: dynamometric tests

The energetic efficiency of each of the motorcycles displayed in Table 1 was calculated with experimental data acquired on an indoor dynamometric bench [15], following a tank to wheel – TTW approach, shown in Fig. 2.

It is worth recalling that the flex fuel motorcycle (Mc4) was fueled with three concentration levels of ethanol. According to these results, the E2Wmotorcycle (Mel) showed the highest energy efficiency, 47.1%, in contrast to the internal combustion engine (Mc2) fueled with E22 gasoline, with an efficiency of 13.36%.

4.2. Electrical efficiency

Steps for electric overall efficiency calculation is depicted in Fig. 1, starting in ELEC-1 to 2, with data from dynamometric tests performed for motorcycle Mel, followed by transmission and distribution energy loss (ELEC-2 to 3), and finishing with the efficiency of primary energy conversion (ELEC-3 to 4). Table 3 summarizes data for the overall chain efficiency for Mel in respect to 2016 data of the Brazilian electrical matrix, calculated by the Technical Conversion Efficiencies TCE.

Data in the first column represents the conversion efficiency of each primary source as seen in point 4 to 3 of Fig. 1, retrieved from previous studies of Brazilian conversion technologies.

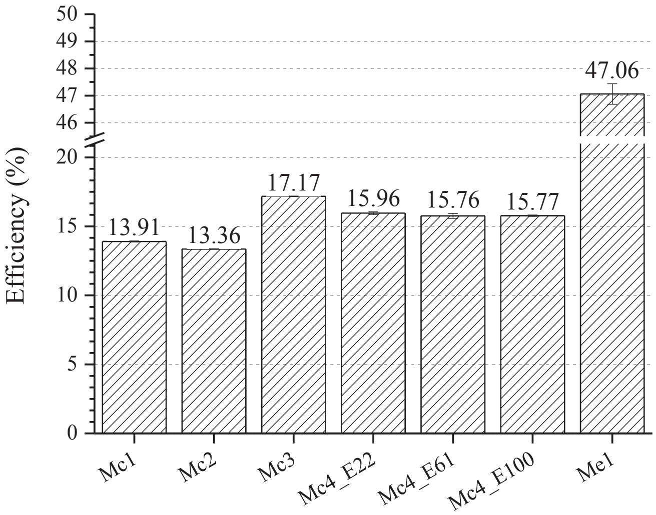

Fig. 2. Measured energy efficiency for blended gasoline and electric fueled motorcycles, as a tank to wheel TTW approach.

According to Câmara [40], Brazilian hydroelectric powerplant efficiency was estimated to reach 80%, after a wide study regarding unit size and age, water level difference, company ownership and geographic location. Wind mills displayed an average efficiency of around 35% [41]. Average efficiency of photovoltaic powerplant was found to be around 15% [42]. Biofuel powerplants are mainly fueled by sugarcane bagasse, followed by several types of residues, as rice hull and wood sawdust, estimated in an overall efficiency of 20% [42].

The non-renewable sources of the Brazilian matrix are predominantly natural gas, followed by oil, and finally by coal and nuclear. Half of the natural gas powerplants in the country operates under high efficiency combined cycles, but the remaining half weights down the average efficiency to approximately 42% [43]. Oil fueled power plants are diesel moto generators, with average 40% efficiency [44]. Coal-fired powerplants are subcritical cycles, and operate with efficiencies below 34%, like nuclear power plants [42].

The overall grid efficiency was calculated by combining transmission and distributions losses [29] (points 3 to 2) to the Brazilian electric matrix share. The measured efficiency of the motorcycle found in the dynamometer tests, point 2 to 1 in Fig. 1, is then accounted in order to reach the final overall efficiency of the electrical motorcycle. That final overall efficiency was found to be 25.5%, practically half of the one measured in the indoor dynamometric test.

Table 4 follows the same prior reasoning but displays the overall chain efficiency for Mel in respect to 2016 data of the Brazilian electrical matrix based on the Physical Energy Content method PEC.

According to the PEC method, the overall efficiency of the electric motorcycle was found to be 32.2%, in opposition to 25.5% from the latter method. The difference between the overall efficiencies relies on the consideration of 100% efficiency for the conversion of hydro, wind and solar power into electricity with PEC, whereas the TCE method employed the actual system value. PEC's approach favors results from renewable electric matrixes, like the one from Brazil.

4.3. Liquid fuels

4.3.1. Gasoline and ethanol

Pre-salt oil extraction efficiency was calculated to be 94.3%, according to Eq (2), using the energy balance value found by Clasen and Agostinho [45]. According to the mass balance released by IEA [46], refineries received 110.1 Mtoe of crude oil, including national production and imports, with an output of 106.5 Mtoe, a conversion efficiency of 96.73%. Energy losses related to gasoline production account for both pre-salt extraction and crude oil conversion in the refineries, leading to an overall efficiency of 91.2%.

Urquiaga and Boodey [39] performed an energy balance for sugarcane ethanol production under Brazilian conditions. They found a picture number of 8.06, analogous to the EROI number, which was assumed here as the ethanol fuel production efficiency of 87.6%, according to Eq. (4).

4.3.2. Internal combustion motorcycles efficiency

Table 5 brings the overall energy efficiency per liquid fueled motorcycle, as the result of a chain calculation, following a Tank-to-Wheel analysis.

4.4. Motorcycle Primary Energy Factor

Table 6 summarizes data from overall efficiency per motorcycle presented in Tables 3–5, and calculates the respective PEF.

Table 3
Electric Motorcycle Mel overall efficiency in the Brazilian context according to the Technical Conversion Efficiencies method TCE.

Technical Conversion Efficiencies method								
Primary source	Point 4 to 3	Point 3 to 2					Point 2 to 1	Point 1
	Conversion	Transmission	Distribution	Total losses	% Brazilian electrical matrix 2016	Overall grid efficiency	Measured efficiency	Overall efficiency
Hydropower	80% [40]	96%	86.5%	66.4%	68%	54.1%	47.1%	25.5%
Wind	35% [41]			29.1%	5.4%			
Solar	15% [42]			12.5%	0.01%			
Natural Gas	42% [43]			34.9%	9.1%			
Biomass	20% [42]			16.6%	8%			
Oil	40% [44]			33.2%	3.7%			
Nuclear	35% [42]			29.1%	2.6%			
Coal	34% [42]			28.2%	2.9%			

Table 4
Electric Motorcycle Mel overall efficiency in the Brazilian context according to the Physical Energy Content method PEC.

Physical Energy Content method								
Primary source	Point 4 to 3	Point 3 to 2					Point 2 to 1	Point 1
	Conversion	Transmission	Distribution	Total grid losses	% Brazilian electrical matrix 2016	Overall grid efficiency	Measured efficiency	Overall efficiency
Hydropower	100% [31]	96%	86.5%	83%	68%	68.4%	47.1%	32.2%
Wind	100% [31]			83%	5.4%			
Solar	100% [31]			83%	0.01%			
Natural Gas	42% [43]			34.9%	9.1%			
Biomass	20% [42]			16.6%	8%			
Oil	40% [44]			33.2%	3.7%			
Nuclear	35% [42]			29.1%	2.6%			
Coal	34% [42]			28.2%	2.9%			

Table 5
Liquid fueled motorcycle (Mc) overall efficiency in the Brazilian context.

	Fuel production efficiency Eq. (5)	Measured efficiency Fig. 2	Overall efficiency Eqs. (6)–(9)
Mc1 (E22)	94.1%	13.9%	13.1%
Mc2 (E22)	94.1%	13.4%	12.6%
Mc3 (E22)	94.1%	17.2%	16.1%
Mc4 (E22)	94.1%	16.0%	15.0%
Mc4 (E50)	89.4%	15.8%	14.1%
Mc4 (E100)	87.6%	15.8%	13.8%

Losses along the fuel chain made all overall energy efficiencies to decrease, with a stronger effect over the electric system. PEF shows how many units of primary energy were consumed to deliver a single unit of converted energy by each of the tested motorcycles. Results show that motorcycles Mc1 and Mc2, fueled with E22 displayed highest energy penalties, with the worst performance found for Mc2, equipped with a simple carbureted fuel feed system (PEF of approximately 8).

E2W motorcycle Mel showed the best performance among all tested vehicles, with a 47.1% measured efficiency, but that result dropped down dramatically when energy losses along the chain were taken into account. Nevertheless, electric motorcycle Mel still is the best option regarding energy performance, with a PEF of 3.1 calculated by the PEC method and 3.9 by the TCE method.

4.5. *PEF evolution from 2010 to 2016*

The methodology described in this work was extended to take into account the evolution of the Brazilian energy matrix from 2010 to 2016 [47], and results for PEF are displayed in Fig. 3.

PEF of the e-motorcycle expressed the variation in the efficiency of the electric matrix along the years, but remained unchanged for the internal combustion motorcycles as the production efficiency of liquid fuels was considered to be constant throughout the analyzed years. This last value was calculated from Table 6 and represents all Mc results, enabling to associate error bars to the average.

4.6. *Motorcycle PEF time projection*

Changes on the PEF value for a 10 years long forecast was assessed here for three scenarios. The reference scenario, according to [48], is based on the assumptions presented in the 10-year energy expansion plan made by the Brazilian Energy Research Company EPE. It is based on the startup from 2021 on of new fast-starting thermoelectric plants, the additional hydro powerplant motorization, reversible plants, batteries and answer on the demand side. The second scenario admits the photovoltaic option to became cost competitive in 2013, reaching approximately US$ 800/kW [48].

The third scenario evaluates the extreme situation of unfeasibility of hydropower projects in a decade time horizon (2028), based on the actual licensing restrictions for new projects, mainly due to socio-environmental impacts. Energy demand would be supplied by new coal-fired powerplants, that display some advantages over NG/LNG fuels because they have low Unit Variable Cost, fuel price indexed only to the national currency, and the existence of huge proved reserves.

Fig. 4 shows the PEF forecast based on the PEC method for a 10 years long horizon.

Reference and photovoltaic scenarios displayed an inverse trend, almost symmetric, but with little differences at the end of the period. The coal-based scenario implied on a significant increase on PEF in the long term.

Table 6
Primary Energy Factor PEF per motorcycle, calculated after data from Tables 3–5.

	Measured efficiency	Overall efficiency	Relative efficiency reduction	PEF
EE1(PEC method)	47.1%	32.2%	34.6%	3.1
EE1(TCE method)	47.1%	25.5%	47.1%	3.9
Mc1 (E22)	13.9%	13.1%	5.8%	7.6
Mc2 (E22)	13.4%	12.6%	6.0%	7.9
Mc3 (E22)	17.2%	16.1%	6.4%	6.2
Mc4 (E22)	16.0%	15.0%	6.2%	6.7
Mc4 (E50)	15.8%	14.1%	10.8%	7.1
Mc4 (E100)	15.8%	13.8%	13.0%	7.2

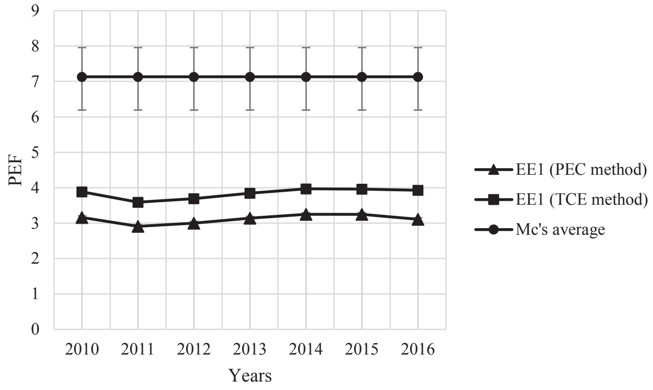

Fig. 3. Evolution of the PEF in the Brazilian energy matrix context from 2010 to 2016.

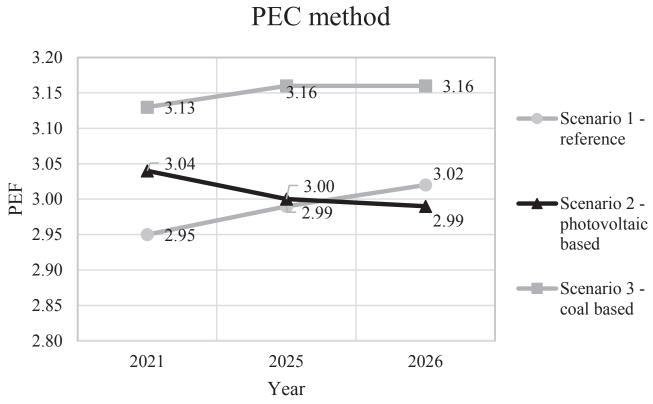

Fig. 4. PEF forecast for the reference, photovoltaic and coal-based scenarios with the PEC method.

Fig. 5 brings the same assessment based on the TCE method.

Reference and photovoltaic scenarios displayed a similar trend and close PEF values. Energy related to the coal-based scenario was once again higher compared to the other scenarios. Photovoltaic scenario seems to lead to a smaller PEF value because it is based on continuously evolving technologies, in opposition to the former ones. All scenarios discard the possibility of overcoming 70% of electricity from hydro sources and point out the need for diversification of the Brazilian matrix.

4.7. Emissions

Emission assessment was developed following the same sequence proposed in Fig. 1.

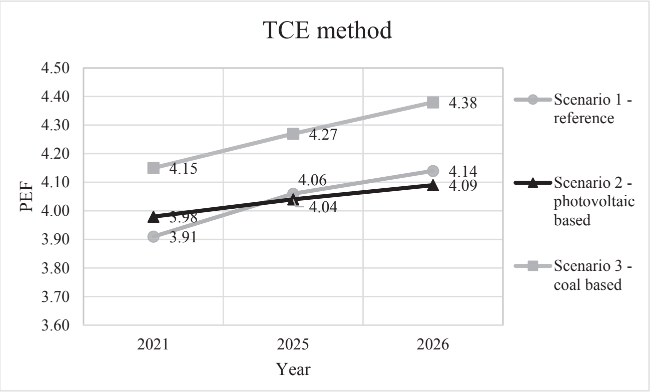

Fig. 5. PEF forecast for the reference, photovoltaic and coal-based scenarios with the TCE method.

4.7.1. Motorcycle emissions

Regulated emissions, namely CO, THC and NO_x from ICE motorcycles and greenhouse gases emissions were measured by the indoor dynamometric tests reported by Daemme et al. [15] for four internal combustion motorcycles (Mc# in Table 1). Results for greenhouse gas emissions are shown in Fig. 6 along the path limited by 1–2 in Fig. 1.

CO_2 emissions were quite similar for the set of engines Mc1, Mc2 and Mc3, but displayed a higher value for MC4, when fueled with E22 or E61. Mc4 motorcycle fueled with E61 presented CH_4 emissions without statistical differences compared to Mc3 and very similar when compared to itself fueled with E22.

Regarding N_2O emissions, there was a change in the emission level related to Mc1 and Mc2 that can be explained due to the presence of a three-way catalytic converter in Mc3 and Mc4 motorcycles.

It is observed a significant reduction in CO and THC in Mc3 and Mc4 motorcycles equipped with electronic fuel injection and catalyst compared to Mc1 and Mc2.

The electric motorcycle was considered to by a zero emission vehicle during its use.

4.7.2. Electrical grid

Emissions of CO_2 equivalent due to electricity generation of the Brazilian electric matrix from the years 2010–2016 [47] are presented in this section and were used to calculate the emissions of the electric motorcycle tested previously. The input data for the electrical matrix composition is the same as in Fig. 3 used for PEF.

The total emissions of the electric motorcycle are presented in g/km in Table 7:

The first column presents emissions from generation sources and concerns the path along points 3 to 4 of the electricity chain in Fig. 1. Emissions from individual sources that compose the electric matrix were based in the previous study performed by Miranda [49] where GHG emissions from the life cycle of Brazilian generation technologies were identified. Total emissions of end-use consumption considered were computed after those data with a 17% surplus due to transmission and distribution average losses [29], points 2 to 3 in Fig. 1. In order to account the total emissions from the motorcycle point of view, the emissions per kWh in the end-use consumption must be converted to grams per rolled km, using the conversion factor of 0.0556 kWh/km [15] of the E2W studied. As shown in Table 7, E2W emissions follow the electric matrix time fluctuation.

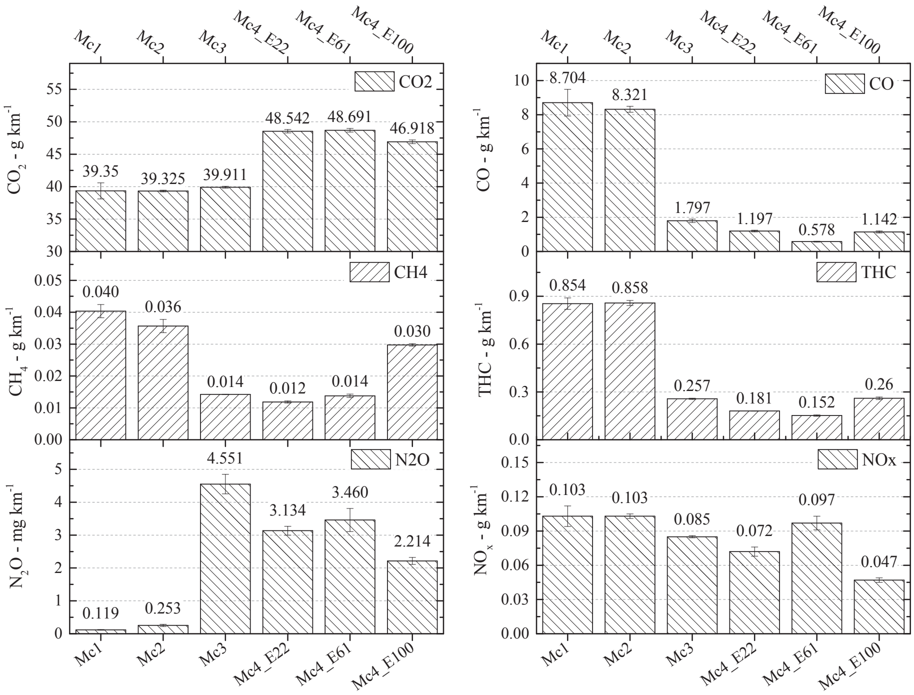

Fig. 6. Measured emissions for blended gasoline fueled motorcycles.

Table 7
Total equivalent CO_2 emissions in the Brazilian energy matrix context from 2010 to 2016 in gCO2eq/kWh.

	Electric generation	Electric consumption	E2W
2010	146.29	176.26	9.80
2011	133.56	160.92	8.95
2012	156.46	188.51	10.48
2013	189.56	228.39	12.70
2014	221.33	266.66	14.83
2015	218.83	263.64	14.66
2016	174.65	210.42	11.70

4.7.3. *Liquid fuels*

CO_2 equivalent emissions for the complete chain in Fig. 1 can be calculated by combining fuel production and motorcycle end use, whose separate contribution is presented in Fig. 7.

According to Walter et al. [50], gasoline emissions due to oil extraction, transport and refinery were estimated as 12.5 kgCO2eq/GJ, corresponding to points 2 to 4 in the gasoline chain in Fig. 1. Sugarcane ethanol emissions were restricted to its production, estimated as 20.47 kgCO_2eq/GJ, points 2 to 3 in ethanol chain in Fig. 1. A weighted average relation was proposed in this paper for each fuel blend, shown in the second column of appendix A-1.[1]

Emissions from gasoline and ethanol production and distribution chain were added on the top of the measured tailpipe emission on the dynamometric tests [15]. Conversion data to expand the fuel production analysis of CO_2 equivalent per kWh to CO_2 equivalent per km sent to the atmosphere from the motorcycle's point of view can be found at the appendices A-1 and A-2.

It should be noted that due to ethanol's renewable character, the emission of CO_2 from its combustion was not considered. This lead the motorcycles fueled with a greater blend of ethanol to be less pollutant.

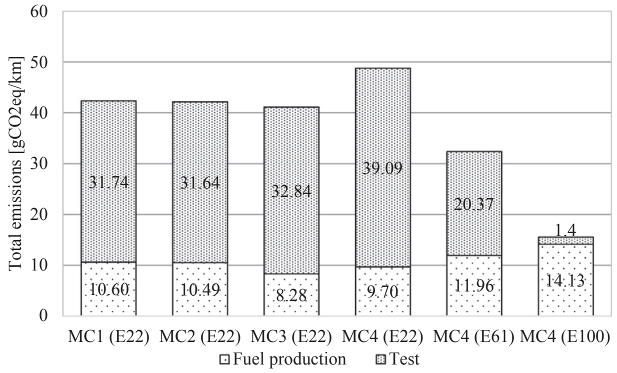

Fig. 7. CO_2 equivalent emission from fuel production and motorcycle use.

4.7.4. *Overall emissions*

The estimated emissions in Table 7 and Fig. 7 are presented in Fig. 8 as a historical analysis of the overall emissions of each motorcycle.

Mc4 fed with E100 competes with EE1 for the 2014 and 2015 period because there was a lower share of hydroelectric plants in the electric matrix, and therefore resorting to more pollutant energy sources. Battery emissions were not accounted in the present work, it is fair to admit that EE1 curve would actually step up and decrease its attractiveness in respect to Mc4 fed with E100. It is worth noticing that the electric motorcycle displayed lower energy consumption and equivalent CO_2 emissions when compared to the set of tested vehicles.

5. Conclusion

This article provided an analysis of the energy efficiency of motorcycles driven by different fuels, by assessing the Brazilian

---

[1] Walter et al. [50] values for gasoline and ethanol production emissions were converted to 45 gCO_2eq/kWh and 73.69 gCO_2eq/kWh, respectively.

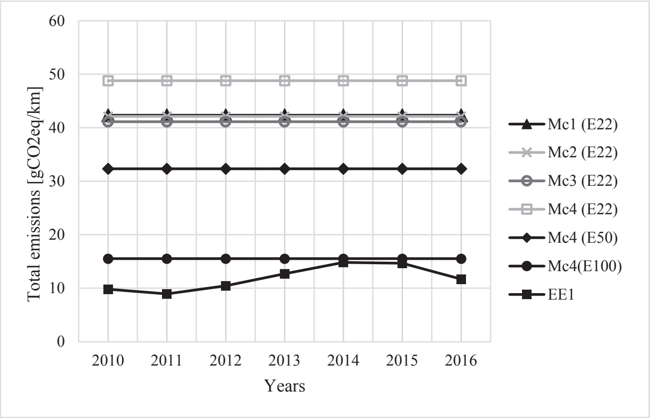

Fig. 8. Motorcycle emission evolution in the Brazilian context from 2010 to 2016.

energy chain for electricity and liquid fuels, starting from the motorcycle use to finish all the way up to primary source conversion. Along this chain it was evaluated energy losses and GHG emissions for the motorcycles tested previously.

Results from dynamometric essays of electric and internal combustion engines motorcycles pointed out a large advantage in energy consumption for electric driven vehicles, but without considering a more comprehensive analysis. Essays showed 47.06% efficiency for electric driven motorcycles and 15.32% in average for liquid fueled engines vehicles, a 3 to 1 ratio in energy conversion efficiency.

A preliminary discussion on existing methodologies was addressed and showed that the bottom-up methodology was the most suited for the present case, with the Primary Energy Factor PEF as assessment parameter. Direct energy losses were estimated to every step throughout the energy pathway, concerning electricity, gasoline and ethanol.

PEF for electric driven motorcycles was found to be 3.1 and 3.9, whenever calculated by the Physical Energy Content PEC or the Technical Conversion Efficiencies Method TCE. The average PEF for liquid fueled motorcycles was found to be 7.1, and the ratio of 2 to 1 in favor of electric driven engines. Results showed that electric driven motorcycles are still more energy efficient for the Brazilian matrix, but a sensitive reduction was found whenever a more comprehensive approach was used to assess the fuel chain.

The Mc4 presented a higher PEF than the EE1. However, from an environmental point of view, the Mc4 fueled with E100 can be an interesting alternative. In 2014 and 2015, the electric motorcycle presented higher emissions due to the lower share of hydroelectricity and consequently the higher insertion of fossil sources. In these years, the Mc4 fueled with E100 and the e-motorcycle have very competitive emissions.

The case study showed that electric driven motorcycles are a viable option in the Brazilian scenario, but it's worth to notice that results are only valid within the specific period and the tested motorcycles. It's though recommend to take into account different scenarios, motorcycles and their test conditions.

Acknowledgements

The authors acknowledge the financial support from CNPq–Brazilian National Council for Scientific and Technological Development, project CNPq 406898/2013-8; Smith Schneider acknowledges the research grant (CNPq-PQ 305357/2013-1), and CNPq – Law 8010.

Appendix

A-1 Fuel characteristics.

Fuel	Emission factor [gCO_2/kWh]	Lower Heat Value [kJ/kg]	Density [kg/L]
E22	51.32	24,940	0.8098
E61	62.50	32,615	0.7765
E100	73.69	39,054	0.7430

A-2 Tested motorcycles fuel economy.

Motorcycle	Fuel economy [km/L]
MC1 (E22)	39.0
MC2 (E22)	39.4
MC3 (E22)	49.9
MC4 (E22)	42.6
MC4 (E61)	36.7
MC4 (E100)	29.2

References

[1] World Energy Council. World energy resources. 2016.
[2] EPA. Global greenhouse gas emissions data. 2015. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.
[3] EIA. International energy outlook. 2016. https://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf.
[4] EPE. Relatório Síntese: ano base 2017. 2018. http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-303/topico-397/RelatórioSíntese 2018-ab2017vff.pdf.
[5] Weiss M, Dekker P, Moro A, Scholz H, Patel MK. On the electrification of road transportation – a review of the environmental, economic, and social performance of electric two-wheelers. Transport Res Transport Environ 2015;41:348–66. https://doi.org/10.1016/J.TRD.2015.09.007.
[6] ICCT. Comparison of leading electric vehicle policy and deployment in Europe. 2016.
[7] Weinert J, Ogden J, Sperling D, Burke A. The future of electric two-wheelers and electric vehicles in China. Energy Pol 2008;36:2544–55. https://doi.org/10.1016/J.ENPOL.2008.03.008.
[8] Cox BL, Mutel CL. The environmental and cost performance of current and future motorcycles. Appl Energy 2018;212:1013–24. https://doi.org/10.1016/J.APENERGY.2017.12.100.
[9] Malik Y, Prakash N, Kapoor A, Au AE. ROLE OF INCENTIVES IN PROMOTING ELECTRIC VEHICLE AMONG INDIAN CONSUMERS. 2016.
[10] Huang SK, Kuo L, Chou K-L. The impacts of government policies on green utilization diffusion and social benefits – a case study of electric motorcycles in Taiwan. Energy Pol 2018;119:473–86. https://doi.org/10.1016/J.ENPOL.2018.04.061.
[11] Zuev D, Tyfield D, Urry J. Where is the politics? E-bike mobility in urban China and civilizational government. Environ Innov Soc Transit 2018. https://doi.org/10.1016/J.EIST.2018.07.002.
[12] Legifrance. Aides à l'achat ou à la location des véhicules peu polluants 2016. https://www.legifrance.gouv.fr/eli/decret/2016/12/30/DEVR1634598D/jo/texte.
[13] BRASIL. Projeto de Lei do Senado n° 780, de 2015 - Pesquisas - Senado Federal n.d. https://www25.senado.leg.br/web/atividade/materias/-/materia/124442 (accessed October 26, 2017).
[14] BRASIL. Frota de Veículos - 2017 2017. http://www.denatran.gov.br/index.php/estatistica/610-frota-2017 (accessed October 25, 2017).
[15] Daemme L, Penteado Neto A, Smith Schneider P, Rocha BP, Piccoli B, Errera M, et al. Study of the energy efficiency and greenhouse emissions from motorcycles powered by electric and internal combustions engines. In: 26th SAE Bras Int; 2017.
[16] Nakata T. Energy-economic models and the environment. Prog Energy Combust Sci 2004;30:417–75. https://doi.org/10.1016/J.PECS.2004.03.001.
[17] Bhattacharyya SC, Timilsina GR. A review of energy system models. Int J Energy Sect Manag 2010;4:494–518. https://doi.org/10.1108/17506221011092742.
[18] Oladokun MG, Odesola IA. Household energy consumption and carbon emissions for sustainable cities – a critical review of modelling approaches. Int J Sustain Built Environ 2015;4:231–47. https://doi.org/10.1016/J.IJSBE.2015.07.005.
[19] Fleiter T, Worrell E, Eichhammer W. Barriers to energy efficiency in industrial bottom-up energy demand models—a review. Renew Sustain Energy Rev

2011;15:3099–111. https://doi.org/10.1016/J.RSER.2011.03.025.
[20] Brandt AR, Dale M, Barnhart CJ. Calculating systems-scale energy efficiency and net energy returns: a bottom-up matrix-based approach. Energy 2013;62:235–47. https://doi.org/10.1016/J.ENERGY.2013.09.054.
[21] Hwang JJ, Chang WR. Life-cycle analysis of greenhouse gas emission and energy efficiency of hydrogen fuel cell scooters. Int J Hydrogen Energy 2010;35:11947–56. https://doi.org/10.1016/J.IJHYDENE.2010.07.148.
[22] Asian Development Bank. Electric bikes in the People's Republic of China : impact on the environment and prospects for growth. n.d.
[23] Nocera S, Cavallaro F. A two-step method to evaluate the Well-To-Wheel carbon efficiency of Urban Consolidation Centres. Res Transport Econ 2017;65:44–55. https://doi.org/10.1016/J.RETREC.2017.04.001.
[24] Woo J, Choi H, Ahn J. Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: a global perspective. Transport Res Transport Environ 2017;51:340–50. https://doi.org/10.1016/J.TRD.2017.01.005.
[25] EURELECTRIC. European commission proposal to revise the energy efficiency directive EURELECTRIC proposals for amendments. 2017.
[26] Adapt Consulting. Determining primary energy factors for electricity. 2016.
[27] Comité Européen de Normalisation. Standard EN 15316-4-5:2007: heating systems in buildings e method for calculation of system energy requirements and system efficiencies e part 4 and 5 space heating generation systems, the performance and quality of district heating and large volume syste. 2007.
[28] Wilby MR, Rodríguez González AB, Vinagre Díaz JJ. Empirical and dynamic primary energy factors. Energy 2014;73:771–9. https://doi.org/10.1016/J.ENERGY.2014.06.083.
[29] ANEEL. Perdas de Energia n.d. http://www2.aneel.gov.br/area.cfm?idArea=801&idPerfil=4.
[30] EUROGAS. Eurogas views on primary energy factor. 2016.
[31] Stoffregen A, Schuller O. Primary Energy Demand of Renewable Energy Carriers: Part 1: definitions, accounting methods and their applications with a focus on electricity and heat from renewable energies. 2014.
[32] Esser A, Sensfuss F. reportFinal report: evaluation of primary energy factor calcula-tion options for electricity n.d.
[33] Boletim ANP. Mensal da Produção de Petróleo e Gás Natural. 2018.
[34] Murphy DJ, Hall CAS. Year in review-EROI or energy return on (energy) invested. Ann N Y Acad Sci 2010;1185:102–18. https://doi.org/10.1111/j.1749-6632.2009.05282.x.
[35] Macedo IC. Balanço das emissões de gases de efeito estufa na produção e no uso do ethanol no Brasil. 2004.
[36] Macedo IC. Greenhouse gas emissions and energy balances in bio-ethanol production and utilization in Brazil. 1996.
[37] Macedo IC, Seabra JEA, Silva JEAR. Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: the 2005/2006 averages and a prediction for 2020. Biomass Bioenergy 2008;32:582–95. https://doi.org/10.1016/J.BIOMBIOE.2007.12.006.
[38] Pimentel D, Patzek T. Ethanol production: energy and economic issues related to U.S. And Brazilian sugarcane. Nat Resour Res 2007;16:235–42. https://doi.org/10.1007/s11053-007-9049-2.
[39] Urquiaga S, Alves BJR, Boodey RM. Produção de biocombustíveis: a questão do balanço energético. 2005.
[40] Camara EA. Um estudo comparativo da eficiência das Usinas Hidrelétricas do Brasil, utilizando análise envoltória de dados – DEA. 2008.
[41] Terciote R. Eficiência Energética de um Sistema Eólico Isolado. 2002.
[42] EPE TM (coordinator). Energia Renovável, hidráulica, biomassa, eólica, solar e oceânica. 2016.
[43] EPE TM (coordinator). Energia Termelétrica, gás natural, biomassa, carvão e nuclear. 2016.
[44] Stuchi G, Taconelli M, Langhi V. Geração termelétrica: principais componentes e tipos de centrais termelétric. 2016. http://www.tcc.sc.usp.br/tce/disponiveis/18/180500/tce-14032016-175537/.
[45] Clasen AP, Agostinho F. Avaliação da eficiência energética do petróleo do pré-sal Brasileiro. In: 6th Int. Work. Adv. Clean. Prod.; 2017.
[46] IEA. Sankey Diagram n.d. https://www.iea.org/Sankey/#?c=Brazil&s=Finalconsumption (accessed January 17, 2018).
[47] BRASIL. MME. Balanço energético nacional (BEN): base year 2016. 2017.
[48] BRASIL. MME. Plano decenal de Expansão de Energia 2026. 2017.
[49] Miranda MM de. Fator de emissão de gases de efeito estufa da geração de energia elétrica no Brasil: implicações da aplicação da Avaliação do Ciclo de Vida. Biblioteca Digital de Teses e Dissertações da Universidade de São Paulo. 2012. https://doi.org/10.11606/D.18.2012.tde-22012013-112737.
[50] Walter A, Dolzan P, Quilodrán O, de Oliveira JG, da Silva C, Piacente F, et al. Sustainability assessment of bio-ethanol production in Brazil considering land use change, GHG emissions and socio-economic aspects. Energy Pol 2011;39:5703–16. https://doi.org/10.1016/J.ENPOL.2010.07.043.