Environmental Footprints and Eco-design
of Products and Processes

Subramanian Senthilkannan Muthu
Editor

Carbon Footprints

Case Studies from the Energy and Transport Sectors

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Environmental Footprints and Eco-design of Products and Processes

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ISSN 2345-7651 ISSN 2345-766X (electronic)
Environmental Footprints and Eco-design of Products and Processes
ISBN 978-981-13-7911-6 ISBN 978-981-13-7912-3 (eBook)
https://doi.org/10.1007/978-981-13-7912-3

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Contents

Prospective Assessment of the Carbon Footprint of a National Power Generation System

Zaira Navas-Anguita, Diego García-Gusano and Diego Iribarren

Abstract The global energy system is typically associated with severe environmental concerns, especially in terms of greenhouse gas emissions. In this regard, the transition to a low-carbon economy requires clean energy solutions for both the electricity and the transport sector. This chapter focuses on the prospective assessment of the carbon footprint of a national power generation system by combining life-cycle assessment (LCA) and energy systems modelling (ESM). Long-term energy planning is facilitated by considering not only a business-as-usual scenario, but also a number of alternative energy scenarios oriented towards (i) the extended operation of non-renewable power generation technologies, (ii) the implementation of novel energy policies on CO_2 capture, energy security and externalities, and (iii) cross-sectoral issues such as the deployment of electric vehicles. Through the case study of the Spanish power generation sector, the convenience of promoting the evolution to highly renewable electricity production mixes is shown.

1 Introduction

Nowadays, climate change is one of the main sustainability concerns from a global perspective. It usually refers to the negative consequences of the greenhouse gas emissions released from the different economic sectors. In this sense, it is important to set new policies and targets in order to mitigate climate change in the following years, which is especially relevant to the energy sector. In fact, the power generation and transport sectors account for around 25 and 14% of the global greenhouse gas emissions, respectively (IPCC 2014).

In Spain, the climate change context is similar. Regarding the power generation sector, 61% of the electricity produced in Spain is non-renewable, whereas the

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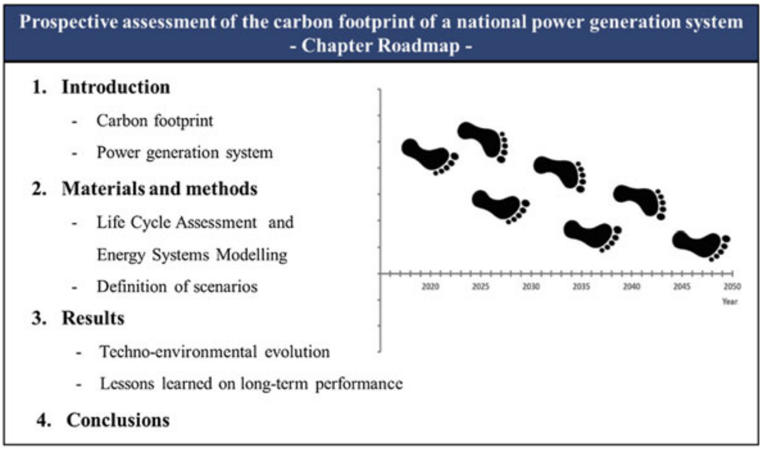
S. S. Muthu (ed.), *Carbon Footprints*, Environmental Footprints and Eco-design
of Products and Processes, https://doi.org/10.1007/978-981-13-7912-3_1



Prospective assessment of the carbon footprint of a national power generation system
- Chapter Roadmap -

1. **Introduction**
   - Carbon footprint
   - Power generation system
2. **Materials and methods**
   - Life Cycle Assessment and Energy Systems Modelling
   - Definition of scenarios
3. **Results**
   - Techno-environmental evolution
   - Lessons learned on long-term performance
4. **Conclusions**

Fig. 1 Structure of the chapter

remaining 39% comes from renewable sources (REE 2019). Actually, the contribution of renewable sources to the Spanish electricity production mix has grown considerably during the last decades. Nevertheless, the electricity demand is expected to be higher in the future, thus being necessary to evaluate the technologies that could satisfy such a growing demand. Moreover, the transport sector should move from a fossil-based system (mainly diesel and gasoline) to a non-fossil-based one with a high share of alternative fuels and vehicles, e.g. electric vehicles (EV), which add an electricity demand to the power generation system.

When planning power generation systems from a long-term perspective, not only techno-economic aspects should be considered, but also socio-environmental issues. In particular, the environmental impact of the electricity produced should be taken into account through the implementation of life-cycle indicators in the power generation model (García-Gusano et al. 2016a). Among the indicators quantified through the life-cycle assessment (LCA) methodology (ISO 2006a, b), the most common one is the global warming impact or carbon footprint (CF). Within this context, this chapter focuses on the prospective assessment of the carbon footprint of the Spanish generation system under alternative scenarios. Figure 1 shows the roadmap of the chapter.

2 Materials and Methods

The goal of this chapter is to prospectively assess the carbon footprint of a national power generation system not only under a business-as-usual (BaU) scenario, but also under alternative energy scenarios oriented towards (i) the extended operation of non-renewable power generation technologies, (ii) the implementation of novel energy policies on CO_2 capture, energy security and externalities, and (iii) cross-sectoral issues such as EV deployment. Emphasis is laid on the evolution of the power generation technology mix as well as on the corresponding evolution of the system's carbon footprint. This is done by applying a combined Energy Systems Modelling (ESM) and LCA approach (Sect. 2.1) through the case study of Spain—a country characterised by a wide-ranging portfolio of power generation technologies—under a varied set of scenarios (Sect. 2.2).

2.1 The ESM + LCA Approach

The numerous ESM tools to assist decision-makers in developing energy plans involve different approaches in terms of interest, procedure, rationale, and method. For instance, it is possible to distinguish between simulation and optimisation models. The former are based on the connections between parameters and variables of technologies and commodities (fuels, materials, emissions), while the latter involve a more powerful calculation based on the minimisation of system costs. Thus, simulation-based models are usually oriented towards backcasting, whereas optimisation-based models are appropriate tools for forecasting. In between, there is a wide range of strategic combinations with the aim of answering "what if" questions, testing new measures, policies and/or technologies, or just exploring the relevance of key drivers in terms of demand or emission reductions.

According to Pfenninger et al. (2014), a key issue in energy systems models refers to scale, understanding in depth the dimensions of time and space. These authors established a three-level scale of decision-making interest. Accordingly, long-term energy planning is associated with low spatial and temporal resolution while providing a perspective oriented towards social aspects of energy systems. In this respect, it is frequently observed that most of the ESM tools focus only on techno-economic optimisation or accounting balances, considering energy flows and economic equilibrium. Environmental aspects are secondary in most energy systems models, if not neglected. In fact, the only environmental consideration usually consists in including the emission factors associated with the activity of the technologies and/or the use of fuels.

Hence, there is a need to broaden the scope of ESM by implementing a thorough sustainability perspective based on robust indicators. In this regard, the combined use of ESM and LCA—a methodology for the comprehensive evaluation of the environmental performance of product systems (ISO 2006a)—arises as a potential solution. For instance, the goal of the NEEDS project (www.needs-project.org) was to evaluate the full—direct and external—costs and benefits of energy policies and future energy systems. Assuming the availability of an optimisation-based energy systems model (e.g. MARKAL/TIMES models), the strategy followed in NEEDS pursued the internalisation of environmental parameters by including extra costs within the objective function to be minimised. Under this paradigm, the concept of externalities was used to deeply include the environmental dimension within the core of energy systems models. This requires externalities monetisation. The ExternE methodology (www.externe.info/externe_d7) was used to obtain the costs associated with the damages (to human health and environment) from electricity production technologies in European countries.

A key concern is the complexity linked to the combination of different areas of expertise: ESM (energy modellers, policy-makers), LCA (environmentalists, chemical engineers), and ExternE (environmental economists, sociologists, epidemiologists). These areas involve different approaches, entities, and rationales since they were conceived for different purposes. Hence, the idea of including in-depth LCA within the kernel of ESM before monetising damages could be a convenient research line. Assuming ESM as the starting point giving the opportunity to perform prospective analyses via techno-economic optimisation, a focus is placed on the (as deep as possible) integration of LCA into ESM. In principle, it would be possible to evaluate prospectively the environmental performance of life-cycle indicators through their robust integration into an energy systems model. However, there are some hurdles such as methodological inconsistencies, differences in temporal and spatial limits, and nomenclature dissimilarities.

The first works talking about the importance of mixing energy models and environmental methodologies appeared in the late 90s of the twentieth century. For instance, Wene (1996) discussed the need for soft-linking in ESM, while later Ekvall (2002) concluded the importance of mixing methodologies in order to broaden the field of LCA. Kypreos et al. (2008) described the main methodological advances behind NEEDS, and Pietrapertosa et al. (2009, 2010) applied these advances to the TIMES-Italy model. Pieragostini et al. (2012) discussed modelling approaches, concluding that the combination of LCA and ESM means an opportunity in the field of energy modelling.

In the field of power generation, Stamford and Azapagic (2014) carried out a prospective LCA of the UK electricity production mix pre-assuming future energy scenarios. Treyer et al. (2014) performed a similar study for the future EU mix but evaluating different life-cycle indicators. Other studies show a higher level of detail regarding the ESM component. For instance, Portugal-Pereira et al. (2016) performed an LCA of the electricity production mix in Brazil by means of a MESSAGE-based model with some indicators partly integrated. Recently, Volkart et al. (2017) developed an LCA study in connection with a TIMES-based model of the Swiss electricity sector, enriching the final results through multi-criteria decision analysis.

A singular advance in the combined field of ESM + LCA refers to the endogenous integration of life-cycle indicators into energy systems models. In this respect, García-Gusano et al. (2016a) endogenously integrated three life-cycle indicators (viz., climate change, human health, and ecosystem quality) into the TIMES-Norway model. This allowed a prospective analysis of the life-cycle performance of power generation in Norway.

In addition to TIMES-based models, alternative ESM frameworks have already been used in ESM + LCA studies. In particular, García-Gusano et al. (2016b) developed a LEAP-OSeMOSYS model of power generation in Spain endogenously integrating three life-cycle indicators (climate change, human health, and resources).

Fig. 2 ESM + LCA methodological approach

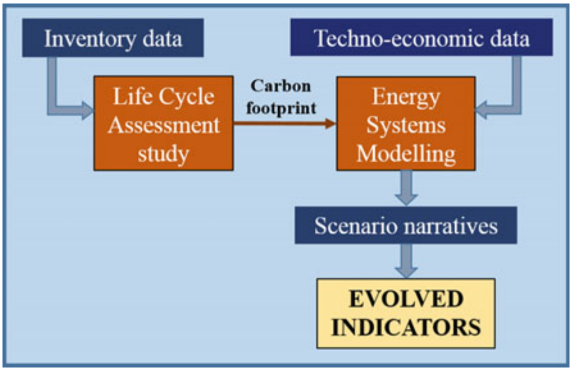


Figure 2 shows the methodological approach followed by the authors, herein adapted to the needs of the study carried out in this chapter. A key and time-consuming task in ESM + LCA studies is data acquisition. In this regard, it is necessary to collect a large number of techno-economic and life-cycle inventory data of each technology involved in the energy systems model. These data are endogenously implemented in the model, thereby enabling the analysis of the evolution of aspects such as the technology mix and the system's carbon footprint under different scenarios.

2.2 Energy Scenarios

The model of the Spanish power generation system detailed in García-Gusano et al. (2016b) is used in this chapter to prospectively assess the system's carbon footprint under several scenarios. The first one is the BaU or reference scenario, while the other five scenarios include alternative specifications regarding the retirement of non-renewable technologies, the implementation of novel policies for the power generation sector, and cross-sectoral issues. With the aim of assessing the environmental suitability of each alternative scenario, the study is based on the difference between a given alternative scenario and the reference (BaU) one in terms of the "evolved" share of renewable technologies and the "evolved" carbon footprint of the power generation system. The main specifications implemented in the model to define the alternative scenarios are explained in Sects. 2.2.1–2.2.3.

2.2.1 Retirement of Non-Renewable Technologies

The contribution of renewable energy technologies to the national electricity production is expected to increase in the coming years. However, nowadays the use of non-renewable sources such as coal and nuclear power is still relevant. In particular, decision- and policy-makers are interested in exploring the role played by coal within the fossil-renewable energy transition. In other words, they are interested in exploring coal extension scenarios. Hence, this chapter includes a “coal extension” scenario considering a 10-year extension for 3560 MW of the existing coal thermal capacity in Spain according to García-Gusano et al. (2018a).

2.2.2 Novel Policies for the Power Generation Sector

In the future, renewable technologies are expected to play the leading role in the Spanish electricity production mix, which would mean a minor role played by non-renewable technologies. Nevertheless, the implementation of CO_2 capture systems (CCS) could significantly affect this prospect by allowing a still significant use of fossil resources. Hence, policy- and decision-makers could be interested in exploring the potential consequences of novel policies forbidding fossil power options unless they include CO_2 capture. In this regard, based on García-Gusano et al. (2016b), the “CO_2 capture scenario” included in this chapter considers that no new fossil capacity installation is allowed beyond 2030 unless CCS options are implemented.

Regarding novel policies for the power generation sector, another relevant point of view could be based on the internalisation of external costs. In this sense, since sustainability is a key component of novel energy policies, the internalisation of externalities could be seen by energy policy-makers as an interesting option to promote a sustainable power generation system. Hence, the “externalities scenario” considers the implementation of the climate change externalities of each power generation technology in the model according to García-Gusano et al. (2018b).

Finally, energy security arises as another key concept concerning novel policies for the power generation sector. In this regard, under an ESM + LCA scheme, García-Gusano et al. (2017a) developed a new energy security indicator—the Renewable Energy Security Index (RESI)—oriented towards policy-makers. Following a life-cycle perspective, RESI measures the importance of indigenous renewable electricity production with respect to the national electricity demand. The use of RESI facilitates setting energy security restrictions that affect the optimisation procedure. In this respect, the “energy security scenario” included in this chapter sets a RESI target above 80% by 2030 according to García-Gusano and Iribarren (2018).

2.2.3 Cross-Sectoral Scenarios

While the harmonised hybridisation of LCA and ESM has mainly been proven in the power generation sector, Navas-Anguita et al. (2018) extended the Spanish power generation model to the road transport system in order to perform the prospective LCA of the increased electricity demand associated with EV penetration in Spain. In this regard, EV penetration arises as a cross-sectoral issue of growing interest to decision- and policy-makers. Figure 3 represents the extension of the methodological approach followed in the EV scenario considered in this chapter. This scenario takes into account a penetration of 14 million EV in Spain in 2050, which approximately

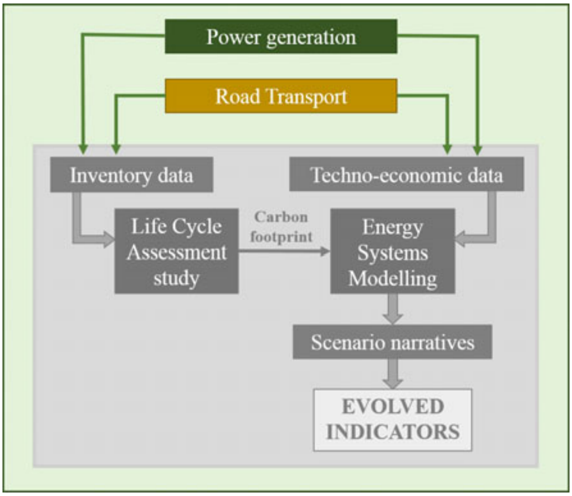


Fig. 3 ESM + LCA methodological approach involving power and transport sectors

means an extra electricity demand of 12.6 TWh (Navas-Anguita et al. 2018). It should be noted that technical issues on EV penetration such as the establishment of complex demand-response schemes within the grid remain out of the scope of this chapter.

Finally, Table 1 summarises the six scenarios assessed in this chapter. The aim of the study is to check the long-term suitability of each alternative scenario by comparing its system's renewability and carbon footprint with respect to the BaU scenario.

3 Results

Three main outcomes are reported in this section: (i) the techno-environmental evolution of the national power generation system under a scenario on the extended use of a non-renewable technology (COAL scenario; Sect. 3.1); (ii) the techno-environmental evolution under three scenarios on novel energy policies (CCS, Ext and RESI scenarios; Sect. 3.2); and (iii) the techno-environmental evolution under a cross-sectoral scenario (EV scenario; Sect. 3.3). Finally, the lessons learned are summarised in Sect. 3.4.

Table 1 List of scenarios under study

Code	Scenario	Description	References
BaU	Business-as-usual	Reference scenario including all current policies	Navas-Anguita et al. (2018)
COAL	Coal extension	10-year extension of existing coal thermal power in Spain	García-Gusano et al. (2018a)
CCS	CO_2 capture	No new fossil capacity installation is allowed beyond 2030 unless CCS options are implemented	García-Gusano et al. (2016b)
Ext	Externalities	Internalisation of climate change externalities	García-Gusano et al. (2018b)
RESI	Energy security	Renewable energy security index target above 80% by 2030	García-Gusano and Iribarren (2018)
EV	Electric vehicle	Increase in the electricity demand due to medium EV penetration (14 million EV in 2050)	Navas-Anguita et al. (2018)

3.1 Techno-Environmental Evolution Under Scenarios on the Retirement of Non-Renewable Technologies

Regarding the potentially extended use of coal power in Spain, Fig. 4 shows the prospective performance of the COAL scenario in terms of the contribution of renewable and non-renewable technologies to the national power generation. As long as coal power plants continue producing electricity, there is no new installation of alternative technologies. Thus, non-renewable electricity production in the COAL scenario increases around 7% during the period 2023–2033 with respect to the BaU scenario (which is also included in Fig. 4 as a reference).

On the other hand, when non-renewable power plants begin to be retired according to their lifespan, the system needs new capacity and production, which is mainly fulfilled by renewable technologies. This leads to a slight increase of approximately 1% in renewable electricity production in the COAL scenario with respect to the BaU scenario until the time horizon (year 2050).

Furthermore, Fig. 5 shows the corresponding evolution of the system's carbon footprint under the COAL scenario. In the period 2020–2033, the coal extension scenario is clearly associated with a significant increase in CF when compared to the BaU scenario. In fact, the COAL scenario involves a 19% increase in the system's CF in 2024. On the other hand, in the long term, a similar CF performance is observed for both the COAL scenario and the BaU one.

It should be noted that the behaviour observed herein for the extension of a specific non-renewable option (i.e. coal power) should not be generalised. For instance, the implementation of extension scenarios for nuclear power in the model has already

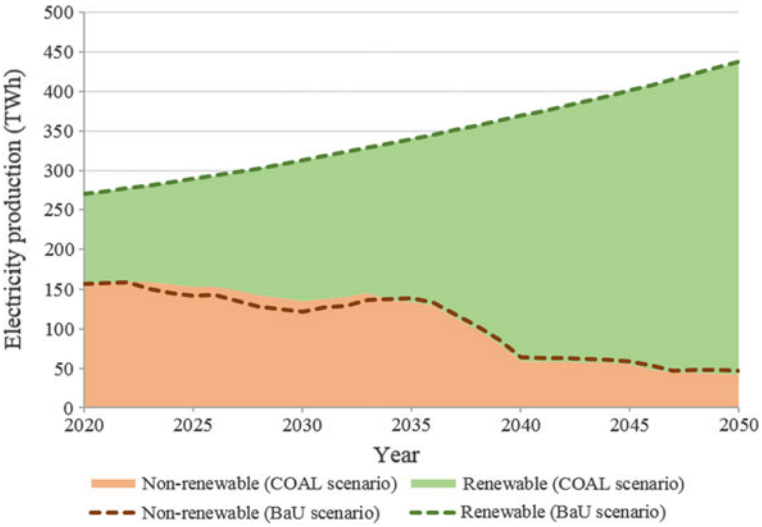


Fig. 4 Scenario "COAL": evolution of the role of renewable power generation technologies in the prospective electricity production mix of Spain according to García-Gusano et al. (2018a)

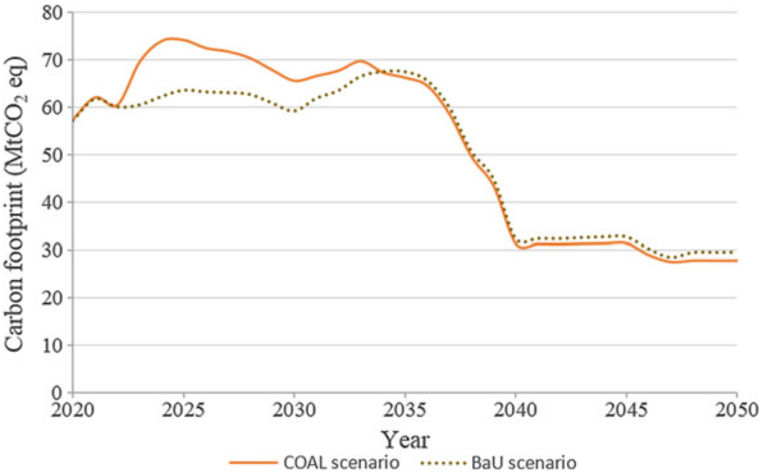


Fig. 5 Scenario "COAL": evolution of the carbon footprint of the Spanish power generation system based on García-Gusano et al. (2018a)

been reported to lead to opposite findings. In such a case, renewable technologies were found to be eventually favoured, enhancing the prospective CF performance accordingly (García-Gusano et al. 2017b).

3.2 Techno-Environmental Evolution Under Scenarios on Novel Energy Policies

Regarding novel policies potentially promoting CO_2 capture solutions for non-renewable power generation, Fig. 6 shows the results of the CCS scenario in terms of the contribution of renewable and non-renewable technologies to the national electricity production. Interestingly, the results show an average increase of 10% in power generation from renewable technologies—rather than from non-renewable technologies with CO_2 capture—with respect to the BaU scenario in the period 2020–2030, even reaching an average increase of 21% in the period 2030–2040. In this respect, the high investment costs of fossil options with CCS finally lead to a preference for the entrance of renewable energy technologies instead of fossil-based technologies with CCS (García-Gusano et al. 2016b).

Furthermore, Fig. 7 shows how the increase in the contribution of renewable technologies to the national power generation translates into a very significant reduction in the system's carbon footprint with respect to the BaU scenario. On average, CF

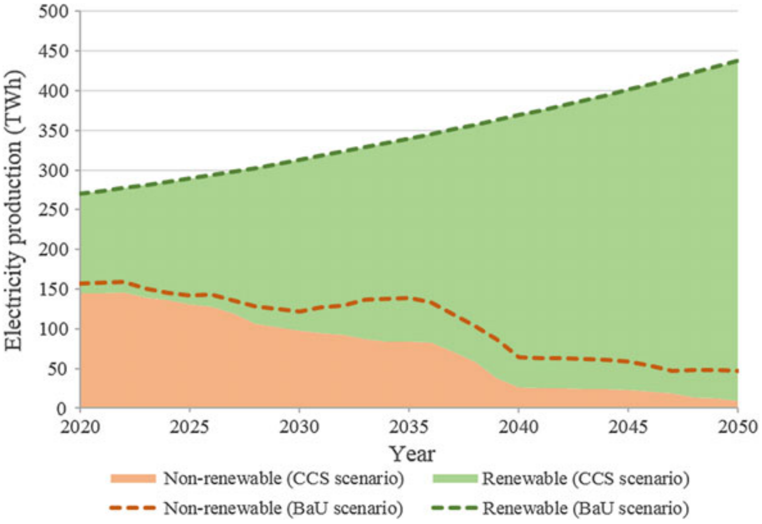


Fig. 6 Scenario "CCS": evolution of the role of renewable power generation technologies in the prospective electricity production mix of Spain according to García-Gusano et al. (2016b)

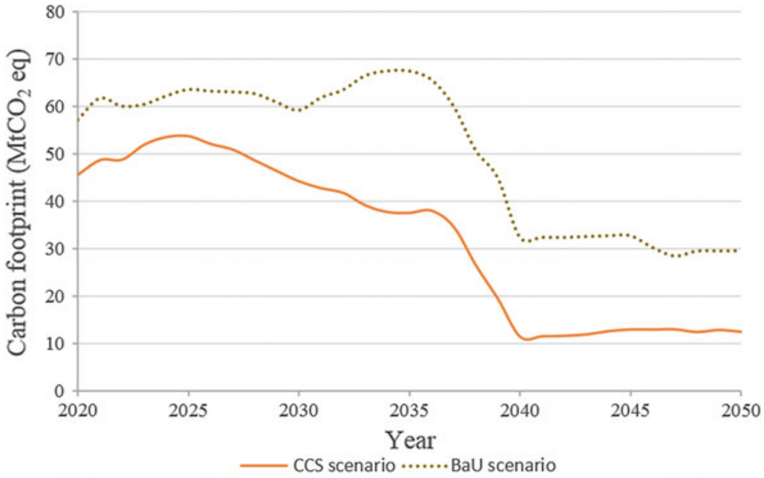


Fig. 7 Scenario “CCS”: evolution of the carbon footprint of the Spanish power generation system based on García-Gusano et al. (2016b)

reductions of 20, 44, and 60% are observed for the periods 2020–2030, 2030–2040, and 2040–2050, respectively.

Regarding the internalisation of external costs as an alternative novel energy policy, Fig. 8 shows the contribution of renewable and non-renewable technologies to the national electricity production when climate change externalities are implemented in the model. As shown in Fig. 8, when compared to the BaU scenario, the internalisation of externalities leads to a faster retirement of non-renewable power plants, which translates into a faster penetration of renewable options. In this regard, average increases of 26 and 13% in renewable power generation are observed in the periods 2020–2040 and 2040–2050, respectively.

Moreover, Fig. 9 shows how the increased share of renewable electricity in the Ext scenario leads to significant reductions in the system’s carbon footprint with respect to the BaU scenario. CF reductions in the period 2020–2035 ranges between 30 and 35%, reaching 60% in the period 2035–2050.

Concerning alternative novel policies based on energy security, Fig. 10 shows the contribution of renewable and non-renewable technologies to the national power generation under the RESI scenario. When compared to the BaU scenario, the implementation of a sensible energy security target leads to a faster and higher penetration of renewables. In fact, an increase of 40% in renewable power generation is observed in 2030.

Furthermore, Fig. 11 shows how the increased contribution of renewable technologies results in significant CF reductions with respect to the BaU scenario. Average CF reductions of 55 and 40% are observed in the periods 2030–2040 and 2040–2050, respectively.

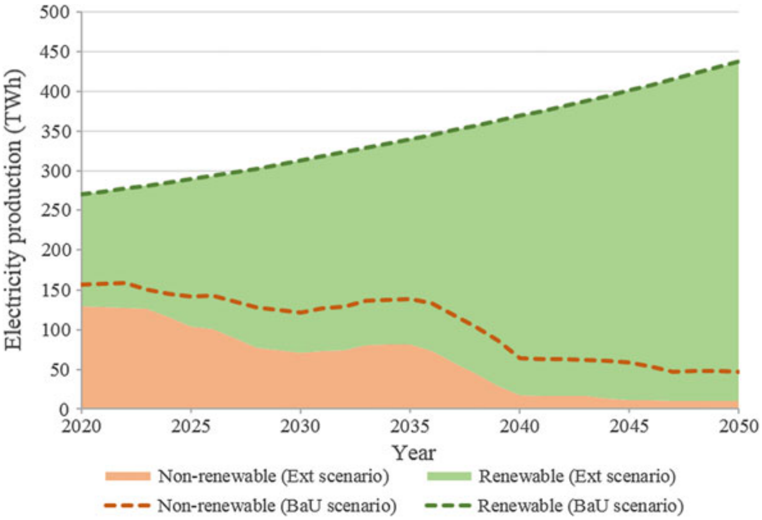


Fig. 8 Scenario "Ext": evolution of the role of renewable power generation technologies in the prospective electricity production mix of Spain according to García-Gusano et al. (2018b)

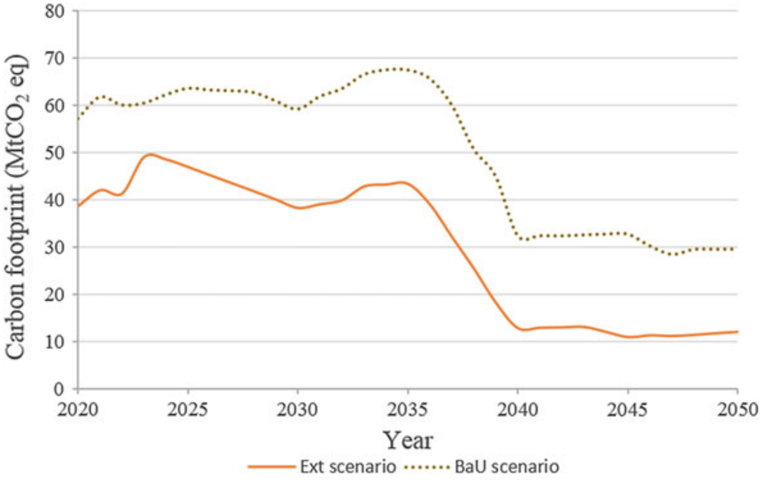


Fig. 9 Scenario "Ext": evolution of the carbon footprint of the Spanish power generation system based on García-Gusano et al. (2018b)

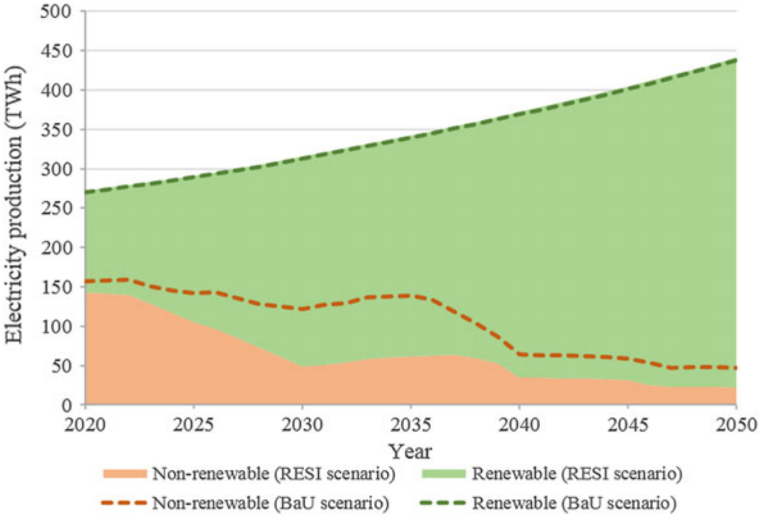


Fig. 10 Scenario "RESI": evolution of the role of renewable power generation technologies in the prospective electricity production mix of Spain according to García-Gusano and Iribarren (2018)

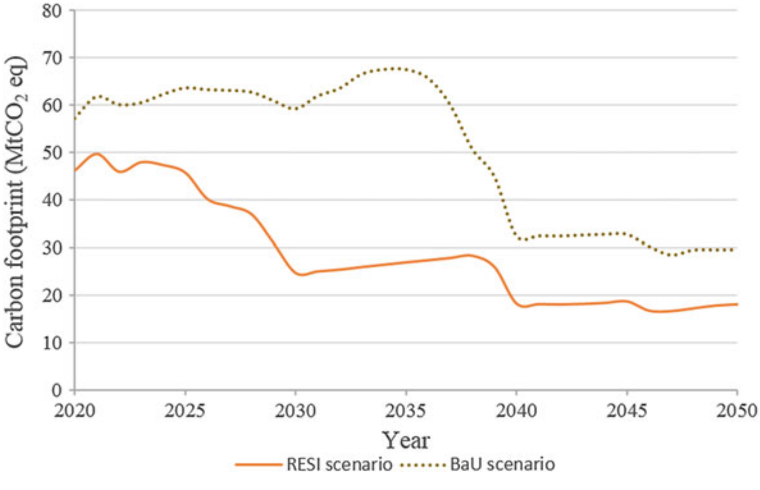


Fig. 11 Scenario "RESI": evolution of the carbon footprint of the Spanish power generation system based on García-Gusano and Iribarren (2018)

Overall, the implementation of novel, sustainability-oriented energy policies in the model is generally found to lead to an increased contribution of renewable technologies to the national electricity production and, as a consequence, to a reduced system's carbon footprint.

3.3 Techno-Environmental Evolution Under Cross-Sectoral Scenarios

As a cross-sectoral issue, the consideration of EV penetration in the power generation model (14 million EV in 2050) involves an increased electricity demand with respect to the BaU scenario. In the EV scenario, this extra demand associated with EV penetration means a low percentage of the total electricity demand (<5% for the whole time frame).

As shown in Fig. 12, the additional electricity demand related to EV penetration is fulfilled by renewable technologies. Furthermore, given the relatively low extra demand, Fig. 13 shows that the system's carbon footprint hardly varies in comparison with the BaU scenario.

Hence, the electricity demand associated with the future penetration of electric vehicles in the Spanish road transport system is expected to be mainly satisfied by a slightly increased contribution of renewable technologies to the national electricity production, with negligible effects on the carbon footprint of the power generation

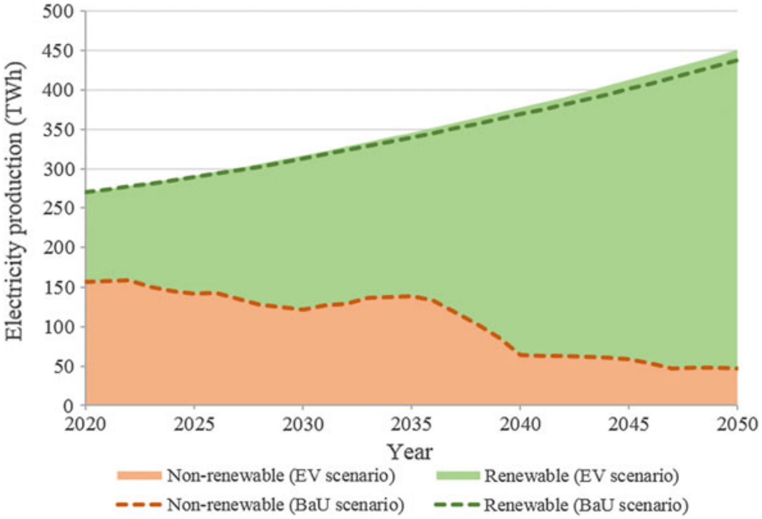


Fig. 12 Scenario "EV": evolution of the role of renewable power generation technologies in the prospective electricity production mix of Spain according to Navas-Anguita et al. (2018)

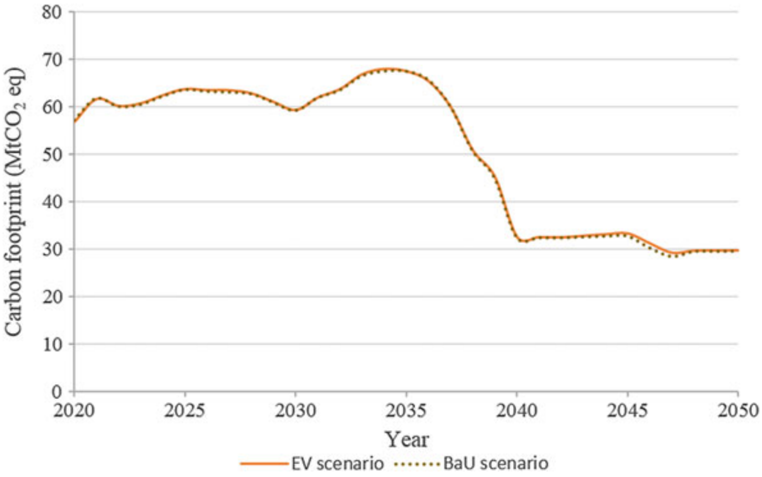


Fig. 13 Scenario "EV": evolution of the carbon footprint of the Spanish power generation system based on Navas-Anguita et al. (2018)

system. Furthermore, according to Navas-Anguita et al. (2018), EV penetration could bring about significant CF benefits within the transport system.

3.4 Lessons Learned

- The prospective assessment of the carbon footprint of the power generation system under alternative scenarios is feasible and can support decision-making processes.
- Extending the use of non-renewable technologies may lead to opposite techno-environmental outcomes depending on the selected option (e.g. coal or nuclear power).
- Coal extension is deemed not to be a sensible option for energy planning in Spain.
- The implementation of novel, sustainability-oriented energy policies generally leads to an increase in the contribution of renewable technologies to the national power generation, as well as to a decrease in the system's carbon footprint.
- When forbidding the installation of new fossil technologies without CO_2 capture, there is a preference for renewable technologies over fossil options with CO_2 capture.
- Policies internalising externalities or setting sensible energy security targets can hasten the retirement of non-renewable power plants, and thus the penetration of renewable options.
- The extra electricity demand associated with the future EV penetration is expected to be satisfied by renewable technologies, with negligible effects on the carbon

footprint of the power generation system but potentially significant CF benefits for the transport system.

Overall, the endogenous integration and prospective assessment of life-cycle indicators into energy systems models has the potential to assist energy policy-makers in performing sensible decision-making processes in the field of long-term energy planning.

4 Conclusions

The synergistic combination of ESM and LCA constitutes a research line of growing interest. The robust integration of life-cycle indicators such as the carbon footprint into energy systems models increases the utility of ESM for decision-making purposes, especially regarding sustainability-oriented energy planning by policy-makers. Nevertheless, it should be noted that the symbiotic story between ESM and LCA is still developing.

Given the current role of the life-cycle global warming impact as a central environmental indicator, prospective carbon footprinting might pave the way for sensible decision- and policy-making processes in the field of energy planning. For instance, through the case study of the Spanish power generation system, this chapter showed the techno-environmental suitability of policies hastening the transition to highly renewable electricity production mixes.

Acknowledgements This research has been partly supported by the Spanish Ministry of Economy, Industry and Competitiveness (ENE2015-74607-JIN AEI/FEDER/UE).

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Energy Valorization of Bio-glycerol: Carbon Footprint of Co-pyrolysis Process of Crude Glycerol in a CHP Plant

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Abstract Increasing biodiesel production has been favored in the last decades due to strict requirements on reduction in GHG emissions in the transportation sector, especially related to diesel fuel. Meanwhile, crude glycerol by-product in the transesterification process has been increased, becoming a bio-based alternative of common glycerin, derived from oil, mainly used in pharmaceutic and cosmetic sectors. However, the current market does not absorb bio-glycerol supply because it should be treated, with noticeable additional costs. Recent researches have tested an innovative use of bio-glycerol as a fuel (Beatrice et al in Appl Energy 102:63–71, Beatrice et al. 2013; Bohon et al in Proc Combust Inst 33:2717–2724, 2011; Quispe et al in Renew Sustain Energy Rev 27:475–493, 2013). This chapter presents the carbon footprint of co-pyrolysis process of crude glycerol in a combined heat and power (CHP) plant following life cycle assessment method and the CF value was compared with the CFs of other common CHP plant. In order to evaluate the influence of the applied allocation procedure, three allocation approaches were followed: substitution method, energy allocation, and exergy allocation. The carbon footprint of the plant varies from 0.14 kg of CO_2-eq/kWh, according to the substitution method, to 0.39 kg of CO_2-eq/kWh, according to the exergy allocation. In each case, the impact is lower than the other common examined technologies. The use stage is the most impactful with respect to the other life cycle stages. However, recovered heat allows to avoid about 0.34 kg of CO_2-eq per kWh of electricity produced. The study aims to evidence the sustainability of energy valorization of crude glycerol.

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S. S. Muthu (ed.), *Carbon Footprints*, Environmental Footprints and Eco-design
of Products and Processes, https://doi.org/10.1007/978-981-13-7912-3_2

Keywords Life-cycle assessment · Biodiesel production · Crude glycerol · Co-pyrolysis · Exergy allocation

Nomenclature

CHP	Combined heat power
El	Electricity
E	Energy [kWh]
Ex	Exergy [kWh]
GWP	Global warming potential [kg CO_2-eq]
IPCC	Intergovernmental Panel on Climate Change
IPRP	Integrated pyrolysis regenerated plant
LHV	Lower heating value [MJ/kg]
NMVOC	Non-methane volatile organic compounds
Q	Heat power [kW]
T	Temperature [°C]
α	Allocation factors
η_{Carnot}	Carnot efficiency

1 Introduction

Notwithstanding the financial crisis began in 2007, worldwide energy demand increases (Moncada et al. 2013). Fossil fuels, such as coal, oil and natural gas, are still the main energy sources, even though the long-term intensive use of fossil fuels is considered not sustainable by scientists. Meanwhile, scientists are worried about global warming, due to the increase of energy-related greenhouse gas emissions into the atmosphere.

On the other hand, biomass and other renewable energy sources (solar energy, wind energy, hydropower, and geothermal power) are sustainable ways to produce energy reducing greenhouse gas emissions (Asdrubali et al. 2015b).

Biofuels are obtained by biomass conversion; they can be used to produce thermal energy and/or electricity, and also as fuels for the transport sector.

The 2003/30/EC Directive (2003) defines the minimum content of biofuels in fossil fuels for transports, i.e., gasoline and diesel, promoting them with incentives and subsidies for EU countries.

The technology to produce biodiesel is simple: biodiesel is usually obtained by the transesterification reaction of vegetable oils or animal fats with methanol. Crude glycerol, which is the main by-product of the transesterification reaction, corresponds to 10% by volume of biodiesel produced.

In Europe, biofuels consumption for transports was about 13 million tonnes of oil equivalents (mtoe) in 2013 and biodiesel share covers about 78% (EurObserver

2014). As a result of the expansion of the biodiesel demand, the global production of bio-glycerol increased from 0.2 to 0.6 megatonnes (Mt) from 2003 to 2006 and reached over 2 Mt in 2011 (Ciriminna et al. 2014).

Until twenty years ago, glycerol was only obtained by the petrochemical synthesis of propylene or soap manufacturing; the main suppliers were oleo-chemical companies (EurObserver 2014). From 1999 to 2009, the biodiesel industry rose from 9 to 64% as a source of glycerol, while fatty acid industry fell down (Gholami et al. 2014).

The demand for glycerol remains unchanged, even if the supply grows; today, the glycerol oversupply leads to low prices in the glycerol market. Before the boom of biodiesel, the price of highly pure glycerol was around 4000€/t in Europe. Ten years later, the price of refined glycerol dropped to 450€/t whereas waste glycerol has no monetary value (Ciriminna et al. 2014).

The reaction of vegetable oil or animal fats with methanol takes place with a catalyst to produce fatty acid methyl esters (called biodiesel) and raw glycerol, with catalyst residues, methanol, salts, and soaps. The main issue is the unsuitability of crude glycerol for industrial application because of many impurities. In fact, the main applications are in the cosmetic, pharmaceutical, and food industries (D'Avino et al. 2015).

Crude glycerol must be purified to be commercialized as glycerin (a solution of almost 95% glycerol, classified in different grades), but the high costs of separating glycerol are disadvantageous for biodiesel plants, in particular for small-medium companies. Alternatively, waste glycerol is disposed of through incineration or it might be used as fertilizer or as food for cattle.

Crude glycerol is an attractive raw material because it is largely available, easily storable, cheap, and renewable, and it is a precursor of many chemical products.

On the basis of the literature review, many researchers have studied innovative processes to convert glycerol into chemicals products via catalytic etherification, hydrogenolysis, transesterification, dehydratation, oxidation, polymerization, acetylation, carboxylation, and moreover, the biological conversion via microorganisms.

Gholami et al. (2014) reviewed the conversion process of glycerol into polyglycerol by the catalyst and its application. Among them, the diglycerol emerged as the most promising value-added product.

Quispe et al. (2013) analyzed the glycerol market, exploring various uses and production processes of crude and refined glycerol. Wichmann et al. (2013) analyzed a metalworking fluid based on glycerol and water, biocide-free, obtaining an interesting cost-effective mixture. Gelinski et al. (2016) also investigated the reuse of crude glycerol mixed with carboxymethyl chitosan and water, aimed to create an innovative biocide-free hydraulic fluid. Rakicka et al. (2016) proposed an eco-friendly technology to produce erythritol from crude glycerol, to be used as a food additive. Dourou et al. (2016) analyzed olive mill wastewater enriched with glycerol as a fermentation medium for yeast strains.

Xu et al. (2016) investigated glycerol use, produced from soy oil, mixed with soy protein for replacing polyvinyl alcohol (PVA) for application in the textile industry.

Bio-based films had a good environmental performance, including those with glycerol derived from soy oil, in comparison with commercial films (Leceta et al. 2014).

Martinez-Hernandez et al. (2014) proved that crude glycerol production can be optimized in a biorefinery. Aiming to better design bioconversion processes in the future biorefinery, Gargalo et al. (2016) implemented a procedure for reducing uncertainty in the environmental assessment. They applied the proposed methodology to crude glycerol conversion in value-added products.

Ekman and Börjesson (2011) studied the production in a biorefinery of propionic acid, derived from crude glycerol and potato juice, in terms of environmental performance. Results showed its potentiality.

Rahmat et al. (2010) reviewed the conversion process of glycerol in fuel additives. Etherification, acetylation, and acetylation reactions were analyzed, focusing on the influence of parameters, as reaction time, catalysts, temperature, etc., on the yield of the process.

Beatrice et al. (2013) investigated the conversion process of glycerol in an oxygenated additive for diesel and biodiesel blends. Afterward, various additive/diesel mixtures were also tested in diesel engine, showing good performance. Good environmental performance of the new additive was proven by Asdrubali et al. (2015a), who assessed the environmental impacts of the glycerol-based additive, burnt in a diesel engine.

Bohon et al. (2011) observed that the direct combustion of glycerol in a furnace was problematic due to harmful emissions; hence, energy valorization of glycerol should follow other paths.

Glycerol could also be reformed to synthetic gas by thermal arc discharge plasma, with satisfactory performance (Tamosiunas et al. 2016).

As previously seen, the products obtained from glycerol can be used as fuel additives; alternatively, glycerol can be a substrate for biogas production (Quispe et al. 2013).

In addition, gasification, pyrolysis, or steam reforming of glycerol permit to obtain hydrogen (H_2).

Pyrolysis process is the thermal decomposition of organic materials in the absence of oxygen, or any other oxidizing agents, at medium–high temperatures (400–800 °C). The process products are gaseous (called synthetic gas, syngas, or pyrogas), liquid (bio-oil or tar), and solid (char), and they are exploitable from an energy point of view. Hence, the pyrolysis process represents an alternative application for the valorization of bio-glycerol. New usages for the exploitation of crude glycerol should be environmental-friendly as well as economically sustainable. In this way, the energetic valorization of glycerol could play a key role in the energy renewable market.

The present work aims at evaluating the energy and environmental profile of the pyrolysis process of crude glycerol in a combined heat and power (CHP) plant. The plant is based on integrated pyrolysis regenerated plant (IPRP) technology (D'Alessandro et al. 2013). In particular, the co-pyrolysis of wood pellet and crude glycerol was analyzed by means of life-cycle assessment (LCA) methodology, considering the entire life cycle of the cogeneration plant.

Although LCA studies of pyrolysis of biomass or waste already exist in the Literature (Di Maria and Fantozzi 2004), LCA analysis of a pyrolysis process of biodiesel-derived glycerol has not yet been performed. This technology has not been extended on a large scale, so existing plants remain pilot or demonstrative units.

Available inventory data of the pyrolysis process are often derived from simulation codes, in place of in situ measurements or experimental data. For this reason, this work—based on a real plant—enables to extend the database of the pyrolysis process of crude glycerol, providing a basis to perform further researches or LCA analysis. Finally, the work provides also the indicators of energy demand and greenhouse gas emissions impact categories, in comparison with other conventional or alternative fuels.

1.1 Pyrolysis of Crude Glycerol

Crude glycerol is low-grade glycerol, which needs to be purified for industrial applications, as shown by the values listed in Table 1 based on recent studies (Gholami et al. 2014). Refined glycerol, used in pharmaceutic, cosmetic, and food applications, is usually obtained by filtration, by chemicals addition or by fractional vacuum distillation with high costs for biodiesel producers. Indeed, biodiesel plants face further costs for treating waste glycerol or for its disposal.

Recent research works shown that crude glycerol can be used as fuel for generating power and/or heat, although the direct combustion of crude glycerol is difficult. Glycerol has high viscosity, high density, high temperature of autoignition, and medium–low heating value (16–21 MJ/kg) (Bohon et al. 2011).

Bohon et al. (2011) realized two experimental systems, a prototypal high-swirl refractory burner and a laboratory-scale refractory-lined furnace, to investigate the feasibility of crude glycerol to fuel a boiler for heat production. Crude glycerol burned successfully in a high-swirl refractory-lined burner and the emissions released during

Table 1 Composition of crude glycerol versus purified and commercial glycerol

Parameter	Crude glycerol	Purified glycerol	Commercial glycerol
Glycerol (% wt.)	60–80	99.1–99.8	99.2–99.98
Moisture (% wt.)	1.5–6.5	0.11–0.8	0.14–0.29
Methanol (% wt.)	23–38	n.a.[a]	n.a.[a]
Soap (% wt.)	3–5	0.1–0.16	<0.002
Ash (% wt.)	1.5–2.5	0.054	0.004–0.007
Acidity (pH)	0.7–1.3	0.1–0.16	0.004–0.007

[a] n.a. not available

combustion of crude glycerol were measured. The presence of a catalyst, used during the transesterification reaction, generates inorganic species, such as sodium and phosphorus, and high emissions of ash during the combustion. Concerns also regard the emissions of volatile organic compounds (VOCs), in particular, the emissions of acrolein, that is a toxic substance, produced at low temperature. The formation of carbonyl emissions was further examined by Steinmetz et al. (2013), the results showed that crude glycerol combustion produced low emissions of acrolein (<15 part per billion by volume) and the other carbonyl emissions were comparable to natural gas combustion.

However, crude glycerol requires a properly designed burner to ensure flame stability and it is not recommended as a boiler fuel, due to high particulate emissions.

The thermochemical conversion of glycerol into syngas through gasification and slow pyrolysis is an alternative way for energy valorization of glycerol. Gasification is partial oxidation of glycerol to produce syngas; while glycerol pyrolysis requires absence or limited amount of oxygen. Various techniques to convert glycerol into syngas have been tested (Yoon et al. 2010).

Low heating value (LHV) of syngas is higher with respect to LHV of natural gas and its use in engines and gas turbines requires the modification of the original architecture (Fantozzi et al. 2007a, b).

Crude glycerol pyrolysis has been studied by various researchers demonstrating the viability of gasification or pyrolysis of glycerol to obtain a synthetic gas, a mixture of carbon monoxide, carbon dioxide, methane, and hydrogen.

Valliyappan et al. (2008) carried out laboratory-scale experiments where pyrolysis of crude glycerol was carried out in a fixed-bed reactor at atmospheric pressure. They studied how the carrier gas flow affected the increase of temperature (from 650 to 800 °C) and the influence of the size of the packing materials on the production of gaseous products. The results show that glycerol can be converted in syngas and the gas yield is influenced by the temperature as well as the diameters of the packing materials. The composition of syngas at 800 °C is shown in Table 2.

Pyrolysis process of crude glycerol in a fixed-bed reactor was also studied by Fernández et al. (2009) using a carbonaceous catalyst to increase the H_2/CO ratio.

Table 2 Composition of gaseous fraction of pyrolysis of crude glycerol at 800 °C in a fixed-bed reactor (Valliyappan et al. 2008)

Compound	Contribution (% mol)
H_2	48.6
CO	44.9
CO_2	1.0
CH_4	3.3
C_2H_4	2.0
C_2H_6	0.1
C_3H_6	0.1
$H_2 + CO$	93.5

The influence of a catalyst, heating by microwave at 800 °C, was investigated and the gas fraction obtained is higher of 80% by volume, rich in hydrogen.

The properties of pyrolysis of glycerol were examined by Dou et al. (2009) with thermogravimetric analysis to understand the decomposition mechanism of glycerol.

Other researchers focused on the co-pyrolysis process of crude glycerol with biomass to increase the gas yield and the heating value of the produced gas.

Skoulou et al. (2012) investigated the fast pyrolysis of glycerol and olive kernel mixture, in an experimental reactor in the laboratory. The olive kernel absorbs the moisture of glycerol. A gaseous fuel rich in hydrogen was produced.

Delgado et al. (2013) also studied the products of the co-pyrolysis of crude glycerol with corn straw residues, identifying the appropriate ratios to obtain the energy recovery. As regards the gaseous products, the crude glycerol contributes to the emissions of light hydrocarbons, whereas H_2, CO, and CH_4 contents are increased because of the presence of corn straw. Manara and Zabaniotou (2013) investigated the fast pyrolysis of crude glycerol with lignite, considering different blends. The increase of temperature promotes the increase of gas fraction, resulting in the highest contribution of hydrogen at 850 °C for a 20% glycerol blend.

1.2 Description of the Plant

The IPRP technology consists of a rotary kiln reactor combined to a gas turbine, fed by the gas produced by slow pyrolysis, as described by Fantozzi et al. (2009). Required heat for pyrolysis process was supplied by exhaust gases of the gas turbine. By-products of the pyrolysis process may be burnt to provide additional heat when required. The plant may be fed with different feedstock such as biomass or waste (Fantozzi et al. 2002). Figure 1 shows the typical process diagram for technology.

The IPRP technology permits to increase the efficiency of cogeneration plants at the microscale: the global efficiency varies from 20 to 30% depending on feedstocks (D’Alessandro et al. 2013).

Previous work (D’Alessandro et al. 2011) analyzed the integration of CHP plant with a biodiesel production plant. Mass and energy balances were based on experimental data carried out by authors on a laboratory scale and on software simulations. The results showed that integrated CHP plant permitted to recover the residues raw glycerol, producing heat and electricity for satisfying energy demand of transesterification plant. The utilization of glycerol may cover the entire electricity demand required to convert biomass in biofuel.

The co-pyrolysis of crude glycerol and biomass was considered for an IPRP pilot plant available at the Department of Engineering of the University of Perugia, in the laboratory located in Terni (Italy) (Fantozzi et al. 2007a).

Fantozzi et al. (2007b) investigated slow pyrolysis process of biomass and waste in a rotary kiln at the University of Perugia.

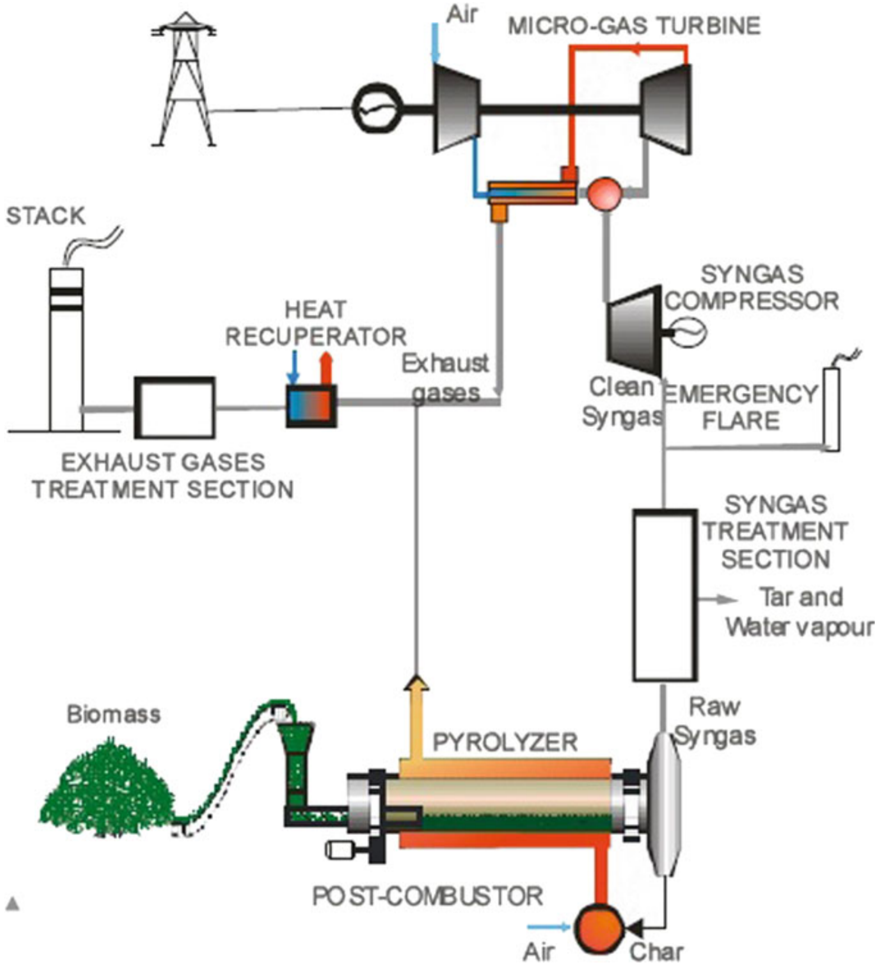

Fig. 1 IPRP layout (Fantozzi et al. 2007a)

Paethanom et al. (2013) scaled the process from laboratory scale to pilot plant. In this work, life-cycle assessment analysis of crude glycerol and wood pellet co-pyrolysis in a IPRP plant was performed.

1.3 Life-Cycle Assessment of Biomass Pyrolysis

Researchers have already studied the impact assessments of operating with bioenergy systems, evaluating the advantages of biomass exploitation in CHP plants.

Boschiero et al. (2016) examined a gasification-CHP plant fed with apple woody residues, proving a remarkable reduction in energy demand and greenhouse gas emissions with respect to reference systems fed with fossil fuels.

Zuwala (2012) analyzed the impacts of co-firing biomass and coal in a CHP plant. The results showed that biomass contribution permits to reduce non-renewable energy demand and CO_2 emissions per unit of thermal energy and electricity produced.

LCA studies of biomass pyrolysis, such as crop residues, lignocellulosic feedstocks, etc., were performed aiming to assess subsequent production of biofuels, compared to conventional fuels, such as fossil diesel or gasoline.

Analyzed the conversion of pyrolysis oil into diesel and gasoline at the biorefinery. Data for inventory derived from simulations of pyrolysis and hydrotreating processes. Global warming potential, abiotic depletion, acidification, and eutrophication potential impact categories were evaluated, and also non-renewable energy demand was quantified. The pyrolysis plant caused the highest contribution to the acidification category and the agricultural stage mainly contributed to the eutrophication category, while the biorefinery was responsible for the high impact of abiotic depletion category and non-renewable energy demand. However, the production of pyrolysis-derived fuels reduced greenhouse gas emissions of about 50% with respect to the production of the corresponding fossil fuels.

Steele et al. (2012) examined bio-oil production from fast pyrolysis of pine chips and the oil combustion in industrial boilers. The global warming potential, human respiratory effects, acidification, eutrophication, smog formation, and ozone depletion potential were evaluated. They evidenced a significant reduction of greenhouse gas emissions produced using bio-oil from biomass (70%) with respect to the use of residual fuel oil.

Hsu (2012) analyzed greenhouse gas emissions and net energy value of pyrolysis-derived diesel and gasoline as a fuel for a passenger car. Greenhouse gases were low in values when the energy required for pyrolysis was supplied from biomass.

The authors evaluated the LCA and the global warming assessment for a small town in central Italy using a small-scale IPRP plant showing sensible benefits with respect to landfilling (D'Alessandro et al. 2011; Di Maria and Fantozzi 2004; Fantozzi et al. 2002).

Zhang et al. (2013) evaluated impacts of bio-oil produced by fast pyrolysis of corn stover and upgraded by hydrotreating and hydrocracking. Iribarren et al. (2012) investigated the bio-oil production and upgrading from poplar biomass. Fan et al. (2011) analyzed the life-cycle impacts of generating electricity from pyrolysis oil combustion.

The aforementioned research works confirmed the reduction of greenhouse gas emissions, using pyrolysis-based biofuels, in comparison with the ones released by conventional fuels combustion.

Table 3 shows some results of recent studies compared with gasoline impacts: Hsu (2012) evaluated indicator of pyrolysis-derived fuel which is 87% lower than the gasoline one. The difference evaluated by Dang et al. is more moderate, about 70% lower than global warning potential due to the gasoline use. Ning et al. (2013)

Table 3 Global warming potential of pyrolysis oil conversion to biofuels per MJ of fuel produced

Authors	Pyrolysis-derived fuel	Gasoline
Hsu (2012)	0.039 kg CO_2/MJ	0.300 kg CO_2/MJ
Dang et al. (2014)	0.28 kg CO_2/MJ	0.93 kg CO_2/MJ
Ning et al. (2013)	0.009 kg CO_2/MJ_{oil}	n.a.

Note n.a. = not available

obtained the lowest value of greenhouse gas emissions from pyrolysis exploitation. The aforementioned results consist of a starting point to better understand the sustainability of the pyrolysis of crude glycerol. However, Peters et al. (2015) observed some critical aspects emerged in the life-cycle chain, such as high electricity consumptions at pyrolysis plant or high impact in values in the eutrophication category due to agricultural phase. Generally, LCA studies of biomass residues and waste pyrolysis follow the same pathway of other LCAs of bioenergy systems (Cherubini et al. 2009). However, few authors carried out LCA analysis on the pyrolysis process, so there is a lack of LCA studies focused on the biomass conversion into syngas.

The present work enables to understand better the environmental performance of a gas turbine fed by pyrolysis syngas. Being based on innovative technology, this paper makes available inventory data as inputs for further researches.

Unlike other works, crude glycerol was considered as feedstock for combined power and heat generation, improving the sustainability of biodiesel production chain.

2 LCA Methodology

The LCA methodology is a useful tool to assess the potential environmental impacts during the life cycle of a product, i.e., good or service (Bonamente et al. 2015). It permits to identify environmental burdens over the whole life cycle following a "cradle-to-grave" approach, from raw materials extraction to disposal phase, or a "cradle-to-gate" approach, limiting the study thereby to the manufacturing phase excluding distribution, use, and disposal (Chang et al. 2014).

The LCA methodology encompasses the entire life cycle of a process to evaluate the potential environmental impacts. This technique, developed since 1973, was standardized by SETAC (Society of Environmental Toxicology and Chemistry) in the 1993.

All input and output flows that cross through the system boundaries are considered, declaring the cut-off criteria and other assumptions. After collecting data, an inventory list is compiled, referred to the function performed by the system. Then the environmental impacts are calculated and the results obtained are interpreted. The LCA analysis supports decisions of designers since it has a holistic approach and it allows identifying the weakness or the benefits in a process chain.

In Literature, LCA analysis of a pyrolysis process of biodiesel-derived glycerol has not been performed because of this technology is not commercialized on a large scale. In addition, the available inventory data of the pyrolysis process derived often by simulation codes, not from direct measurements or experimental data.

For this reason, this work enables to extend the database of the pyrolysis process of crude glycerol, providing a basis to perform further researches or LCA analysis. The work provides also the indicators of energy demand and greenhouse gas emissions impact categories, for comparison with other conventional or alternative fuels.

The LCA method is a systematic procedure, standardized by ISO 14,040 and 14,044 (ISO 2006a, b). It is composed of four stages: (1) goal and scope definition; (2) life-cycle inventory analysis; (3) life-cycle impact assessment; and (4) life-cycle interpretation.

The interpretation of results permits to make conclusions, identifying major contributions and relevance of the impacts, in order to take decisions on improving processes chain. If necessary, the analysis is reviewed to meet the goal of the study.

In this study, the environmental impacts were calculated with the IPCC method.

2.1 Goal and Scope Definition

The aim of the study is to evaluate the environmental impacts of power generation by the IPRP technology fueled with crude glycerol and wood pellets. The functional unit is one kilowatt-hour of electric energy (kWh_e) produced by the plant considering one year as a temporal horizon.

The environmental impacts were evaluated with IPCC GWP 2007 method with a time horizon of 100 years (Hischier et al. 2010).

The use phase corresponds to the production of electricity of the IPRP plant, by means of the conversion of crude glycerol mixed to biomass to syngas.

Results were evaluated by means of SimaPro version 7.3 software (Prè Consultants, The Netherlands) (Herrman and Moltesen 2015).

In addition, the production of one kWh of electric energy was investigated, with exergy allocation, considering different technologies, fossil fuel, and biofuel (natural gas burned in a 160 kWe CHP plant; natural gas burned in a mini-CHP plant; natural gas burned in a microgas turbine 100 kWe; natural gas burned in a 50kWe lean burn CHP plant; and biogas burned in a microgas turbine 100 kWe).

Similar system boundaries were considered for the aforementioned plants, in order to be compared with the system under study. Data for the CHP plants were derived from Ecoinvent database.

2.2 System Boundaries

Life-cycle assessment was performed for biomass and glycerol-derived syngas, produced in an IPRP plant, considering the pilot plant in the laboratory of the University of Perugia sited in Terni (Italy). The life cycle is composed of three main phases:

1. the construction of the plant;
2. the use phase at the IPRP plant;
3. the end of life, i.e., the dismantling of the plant.

The life time of the plant is assumed to be 20 years; life span was estimated considering plants with similar size (Energy and Strategy Group 2012).

Since it was assumed that the plant operates for 7000 h per year, the annual electricity production is 560 megawatt hour (MWh).

The crude glycerol derived from the conversion process of rapeseeds oil to rape methyl esters, as shown in Fig. 2. After cultivation and harvesting, seeds are sent to the mill, transported by lorries. The rapeseeds are crushed and pressed to extract the raw oil. Then, the raw oil is passed to the transesterification reactor with sodium hydroxide and methanol; after the time of reaction, methyl esters are separated from crude glycerol. Data about biodiesel production were gathered from the Literature (González-García et al. 2012). In addition, to better understand the role of methanol process in the biodiesel production, further study was consulted (Kiwjaroun et al. 2009) (Fig. 3).

According to Jungbluth et al. (2007), the allocation of the environmental impacts is based on the economic value of biodiesel and crude glycerol. Thus, 13% of the overall environmental load is allocated to the glycerol flow.

Wood sawdust is derived from wooden material; industrial residual wood is dried to a moisture of 10%. Data about sawmill processes are derived from Ecoinvent database (Werner et al. 2007). Figure 4 shows a flowchart of the involved processes.

Glycerol is transported to the IPRP plant by a lorry as well as the wood sawdust, and then a glycerol–sawdust mixture is produced at the plant and pelletized to facilitate the feeding phase. The analysis considers a mixture of 20% raw glycerol and 80% wood in the pellet.

Pellets are contained in a hopper and, through a screw conveyor fed to the rotary kiln reactor, that is inside a refractory oven. Biomass is thermally converted in the reactor into syngas, char, and tar. The heat required for the pyrolysis process is recovered from the exhaust gases of the microgas turbine and the post-combustion of pyrolysis by-products.

Syngas, tars, and water vapor from the reactor are conveyed to a cleaning section, composed by a cyclone and a wet scrubber, where the gas is cooled through water injection. Tars and water are condensed and removed, and gas is cooled and cleaned. Then, the cleaned syngas is conveyed to the microgas turbine that generates electric power, distributed to the grid.

The exhaust gases pass through a heat exchanger to recover heat, used for hot water production for heating purposes. Before being expelled to the atmosphere,

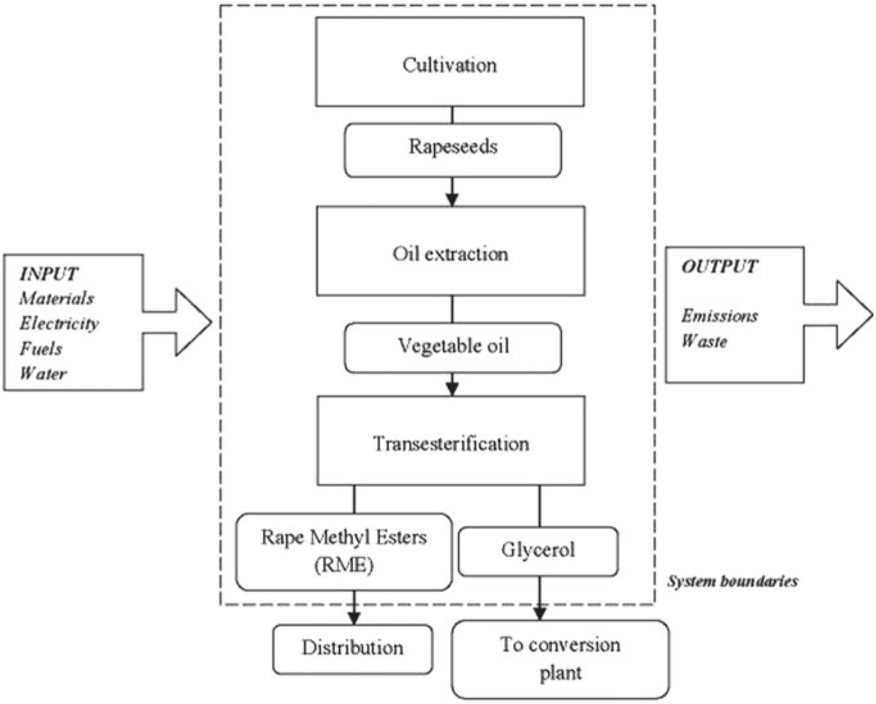

Fig. 2 Flowchart of crude glycerol production at the biodiesel plant

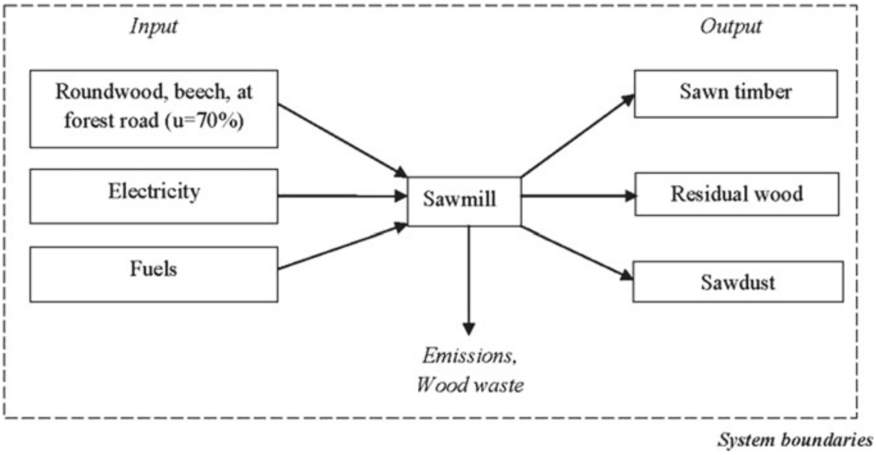

Fig. 3 Flowchart of sawmill processes

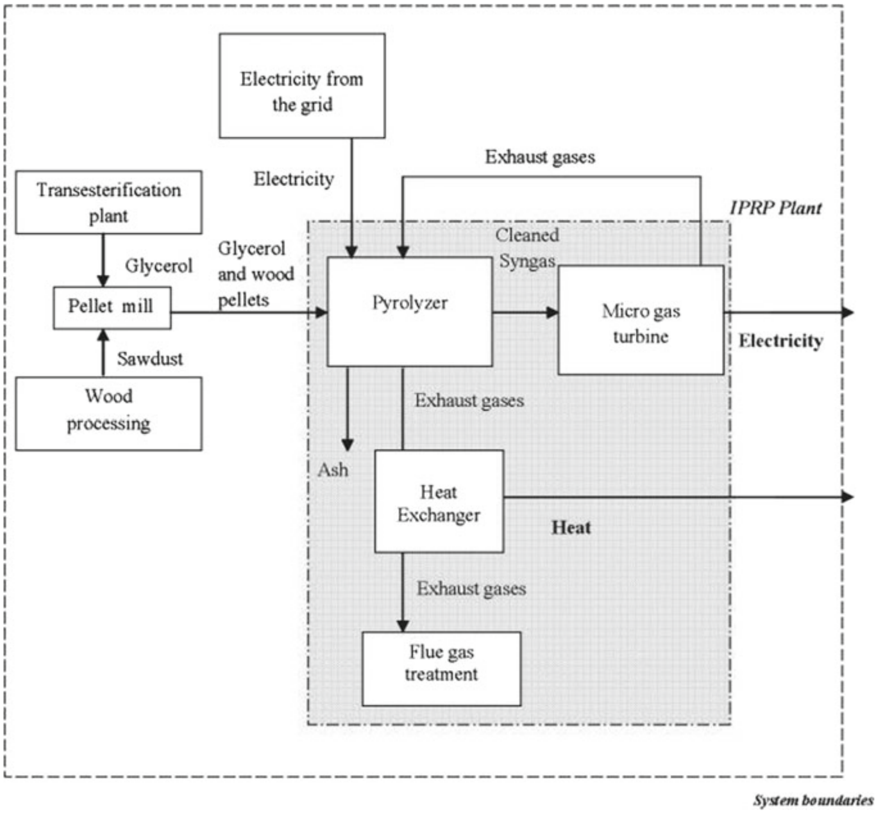

Fig. 4 Flowchart of investigated system

the exhaust gases of the plant are sent to treatment section, where particulates are removed.

Figure 5 shows the analyzed system: the system boundaries extend from the production of glycerol and the production of wood pellets to the electricity and heat cogeneration. The construction phase of the IPRP plant is also considered, within its disposal phase.

The life cycle is subdivided into three main stages: the construction phase (construction of the plant), the operation phase (biomass production, pyrolysis process, and power generation at IPRP plant), and the end of life of the plant (disposal of the plant).

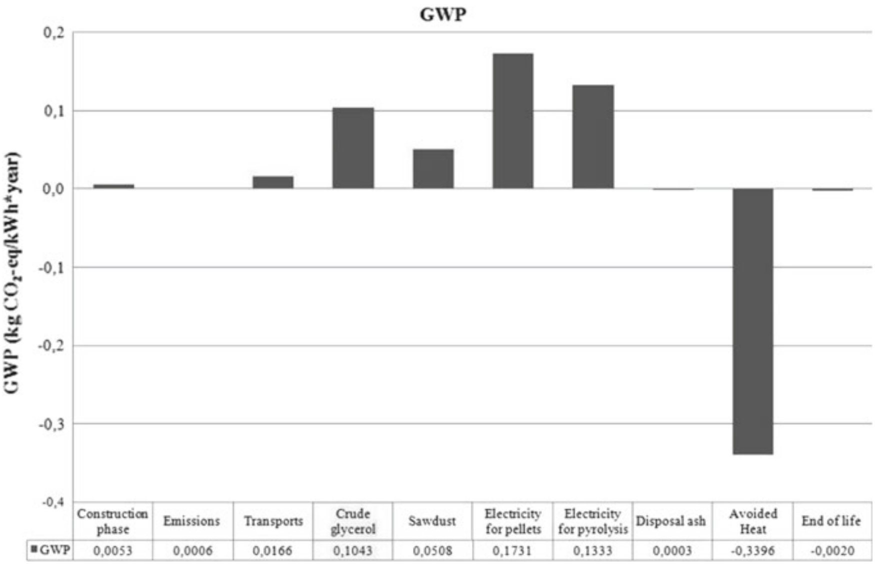

Fig. 5 IPCC method: GWP values per kWh per year for each process involved in the life cycle

2.3 *Life-Cycle Inventory*

Data about the materials used for plant construction and data about the plant operation were obtained from the technicians at the Department of Engineering, that run the pilot facility shown in Fig. 4. Data for the production process of construction materials were gathered from Ecoinvent database (Kellenberger et al. 2007).

In the case of a lack of information, data were derived from Ecoinvent database or from Literature, in particular from Paethanom et al. (2013) and D'Alessandro et al. (2011). Both transport distances of biomass and of glycerol were assumed to be 100 km.

Since electricity and heat are generated at the facility, the environmental impacts are allocated according to the substitution method.

The materials requirements for the construction of plant are shown in Table 4 according to the requirements of the pilot unit shown in Fig. 2. The inventory of construction phase relates to the supply of the materials, from raw materials extraction to the transport to the site of production and manufacturing.

As previously said, the transesterification plant produces methyl esters (90% by mass) and crude glycerol as a by-product (10% by mass), that is sent to the IPRP plant for energy production. It was assumed that the production of biodiesel fuel is located at 100 km from the plant site. The inventory data for the production process of crude glycerol are shown in Table 5.

Because of a lack of direct information from biodiesel producers, the input flows are based on the average values of a biodiesel plant in Europe, gathered from the

Table 4 Materials requirements for plant construction

Materials	Mass (kg)
Steel	16,000
Stainless steel	3700
Refractory material	5400
Copper	570
Aluminum	210
Cast iron	80
Galvanized iron	210
Crude iron	120
Paper	20
Rock wool	40
Silicon sheet	250
Polyvinyl chloride	140
Expanded polystyrene	10

Table 5 Inventory data for the production process of 1 kg of crude glycerol

Processes	Amount	Unit
Inputs		
Rape oil	0.1326	kg
Methanol	0.1168	kg
Electricity	0.1	kWh
Natural gas	0.004	MJ
Transport by lorry 20–28 t	0.0633	tkm
Water	0.023	kg
Sodium hydroxide	0.000233	kg
Hydrocloric acid	0.0017	kg
Emissions to air		
Carbon dioxide, biogenic	0.24	kg

literature (González-García et al. 2012). The inventory data are allocated according to the market price (Jungbluth et al. 2007). Data for the electricity production are taken from the Ecoinvent database, referred to Italian electric production mix. Furthermore, it was supposed that the rapeseeds were cultivated in Northern Italy, and then they were transported to the oil mill by lorry, traveling a distance of 500 km. The emissions of carbon dioxide are derived from the carbon balance.

It was assumed that wood sawdust is derived from a sawmill; the main product of the sawmill processes is a sawn timber and the sawdust is a by-product (about 6% of mass outputs); data are reported in Table 6. Inventory data were derived from Ecoinvent database (Werner et al. 2007).

Table 6 Inventory data for the production of 1 kg of sawn timber at sawmill

Processes	Amount	Unit
Inputs		
Electricity at grid	0.0655260	kWh
Diesel combusted in industrial boiler	0.0010291	l
Kerosene combusted in industrial boiler	0.0000054	l
Liquefied petroleum gas combusted in industrial boiler	0.0000003	l
Gasoline combusted in equipment	0.0001735	l
Softwood logs with bark	0.0037820	m^3
Product and co-products		
Sawn timber	1	kg
Sawdust	0.11863	kg
Pulp chips	0.63511	kg
Bark	0.26098	kg
Emissions to air		
Particulates	0.001663	kg
Emissions to soil		
Bark	0.026877	kg
Waste to treatment		
Wood waste	0.00073101	kg

Wood sawdust and crude glycerol are transported from the site of production to the site of IPRP plant, at a distance of 100 km by a lorry. The transport operations correspond to 0.099 transported per kilometer (tkm).

Wood sawdust and glycerol were assumed to be mixed and compressed at the plant. It was supposed that pellets are produced with a pellet mill machine at the plant; glycerol/wood pellets were composed of 20% of glycerin and 80% of wood sawdust. Since this process is similar to the wood pellet production, the electricity consumption for the mill operation is estimated to be 0.077 kW/kg of dried matter pressed, derived from the Literature (Jungbluth et al. 2007). It was assumed a drying treatment for the biomass before pelleting at the plant, with residual heat from the IPRP facility.

The glycerin/wood pellets are characterized by moisture content of 11% and low heating value equal to 17.89 MJ/kg on a dry basis. The pellets feed the pyrolyzer with a continuous supply of 79 kg/h.

The electricity consumptions for the operation of the pyrolysis reactor correspond to 16.4 kWh and the microturbine generates 80 kW, with an estimated electrical efficiency of the microturbine about 27%.

Synthetic gas from the pyrolyzer is mainly composed by hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2) and methane (CH_4), and other hydrocarbons.

Table 7 Composition of syngas from experimental tests

Compound	% volume
H_2	33
CO	32
CH_4	8
CO_2	8

The composition of syngas is shown in Table 7, based on laboratory measurements of crude glycerol pyrolysis, carried out by CIMIS at the University of Perugia.

The clean syngas (24 kg/h) is sent to the microturbine while char and tars are burned to provide heat, for cogeneration and for biomass drying. Tars are removed from syngas by liquid–solid scrubbing and filtering and are assumed to be about 35% by mass of the biomass yield, as derived by the laboratory measurements.

The ashes (1 kg/h) leave the reactor and they are disposed of landfilling.

According to the plant layout (Fig. 1), the exhaust gases from the turbine are sent back to the pyrolyzer to supply heat for pyrolysis process throughout char post-combustion, below the reactor in the refractory chamber, to provide oxygen for combustion, given the equivalence ratio of the gas turbine.

Exhaust gases from the plant are sent to the recuperator where heat is recovered for heating purposes and finally to a biomass dryer and eventually to strack.

Emissions to the air were estimated from the syngas composition and the stoichiometric reactions (1, 2, 3):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{1}$$

$$2CO + O_2 \rightarrow 2CO_2 \tag{2}$$

$$2H_2 + O_2 \rightarrow 2H_2O \tag{3}$$

It was assumed that the combustion was complete (no CO emissions) and the other emissions as nitrogen oxides, methane, and non-methane volatile organic compounds (NMVOC) were considered similar to those of natural gas combustion. Particulate matter is not accounted since it was removed from exhaust gases by filtering section.

The mass and energy flows of the pyrolysis process and of power generation are summarized in Table 8, related to 1 kWh of electric energy produced by the microgas turbine.

As regards the construction phase and the end of life of the plant, it was assumed that the environmental impacts related to the infrastructure of the plant remain constant during the entire life span. Hence, the estimated impacts were distributed over the lifetime, starting from the construction of the plant.

At the end of life, the processes for the disposal of materials were taken account, distinguishing between the disposal to landfill or recycling. Table 9 shows the end-of-life scenarios assumed for the construction materials of the IPRP plant.

Table 8 Inventory data per functional unit for the IPRP plant

Processes	Amount	Unit	Data source
Inputs			
Wood sawdust	0.79[a]	kg/kWh_e	Estimated from mass balance of the plant
Crude glycerol	0.20[a]	kg/kWh_e	Estimated from mass balance of the plant
Transports to the plant	0.099	tkm/kWh_e	t per kilometer estimated from a standard distance of 100 km
Eletricity for pellets production	0.076	kWh/kWh_e	Estimated from Literature (Jungbluth et al. 2007)
Electricity for pyrolysis (medium voltage)	0.205[a]	kWh/kWh_e	Energy balance of the plant
Output to techosphere			
Electricity	1[a]	kWh/kWh_e	Energy balance of the plant
Ashes	0.015[a]	kg/kWh_e	Estimated from mass balance of the plant
Tars	0.35	kg/kWh_e	Estimated from laboratory measurements
Emissions			
Carbon dioxide, biogenic	0.24	kg/kWh_e	Calculation from the composition of syngas
Nitrogen oxides	0.00016	kg/kWh_e	Estimated from emissions factor of combustion of natural gas (32 mg/MJ)
Methane, biogenic	0.0000272	kg/kWh_e	Estimated from emissions factor of combustion of natural gas (5.4 mg/MJ)
NMVOC	0.00000302	kg/kWh_e	Estimated from emissions factor of combustion of natural gas (0.6 mg/MJ)

[a] The measurements were carried out during daytime experimental tests (three measures per day) with an uncertainty lower than 0.5%

It was supposed that a certain amount of steel, refractory material, copper, aluminum, iron, and paper were recycled, whereas the remaining waste was sent to the landfill.

As previously said, ash was intended to landfill, and tar and char were reused to provide heat for drying biomass.

Each unit of electric energy produced, for an operating life of 140,000 h, brings the environmental impacts of each process involved. The overall impact is the sum of the impacts estimated in each life-cycle stage.

The production of 1 kWh of electric energy from other common CHP technologies was investigated considering different gaseous fuels, such as natural gas and biogas.

Table 9 Disposal scenarios of the construction materials

Materials	Disposal	Recycling (%)
Steel	Landfill	90
Stainless steel	–	100
Refractory material	Landfill	90
Copper	Landfill	90
Alluminum	Landfill	90
Cast iron	Landfill	90
Galvanized iron	Landfill	90
Crude iron	Landfill	90
Paper	–	100
Rock wool	Landfill	–
Silicon sheet	Landfill	–
Polyvinyl chloride	Landfill	–
Expanded polystirene	Landfill	–

Data for the CHP plants are derived from Ecoinvent database and they were evaluated with SimaPro v.7.3 software, likewise the IPRP plant. For the other plants, the same system boundaries are considered, in order to be more comparable with the system under study.

2.4 Allocation

In this study, the substitution method was applied: the main product is electric energy and the coproduct heat, recovered from the exhaust gases of the plant, substitutes the heat produced by natural gas burned in a boiler. The amount of recovered heat, equal to 99 kWh, is associated to the process "*Heat, natural gas, at boiler modulating* <100 kW/RER *U*" in the SimaPro library, based on the Ecoinvent database.

In order to evaluate the influence of the approach applied to the calculated impacts, other approaches were considered.

In the exergy approach, the allocation method is based on exergy content of the electricity and heat outputs, to consider the quality of energy. Since the other contributions of exergy flow, such as the potential, kinetic, and chemical exergy, were assumed negligible, only the exergy associated with the heat transferred was considered. The exergy content of heat flow ($\mathrm{Ex}_{,\mathrm{heat}}$) is calculated according to the Carnot cycle efficiency (η_{Carnot}) as shown in the Eqs. (4) and (5):

$$\mathrm{Ex}_{,\mathrm{heat}} = Q * \eta_{\mathrm{Carnot}} \tag{4}$$

$$\eta_{\mathrm{Carnot}} = 1 - \frac{T_0}{T}. \tag{5}$$

Table 10 Allocation factors

	Electricity (%)	Heat (%)
Exergy	80	20
Energy	45	55

Table 11 Environmental impacts per kWh of electricity produced

Phase	GWP (kg CO_2-eq)
Construction phase	0.005
IPRP plant—use phase	0.14
End of life	−0.002
Total	0.14

where Q is the available heat, T_0 is the environment temperature, and T is the temperature of the heat source.

In the heat exchanger, the exhaust gases transfer heat to the water stream. The calculation is based on the following assumption: hot water produced at the mean temperature of 80 °C (Heck 2007) and the environment temperature equal to 20 °C.

Likewise, in the energy approach, the allocation factors are based on the energy content of electricity and heat outputs.

The allocation factors of electricity and heat are calculated by Eqs. (6) and (7):

$$\alpha_{\mathrm{el}} = \frac{E_{\mathrm{el}}}{E_{\mathrm{el}} + E_{\mathrm{heat}}} \tag{6}$$

$$\alpha_{\mathrm{heat}} = \frac{E_{\mathrm{heat}}}{E_{\mathrm{el}} + E_{\mathrm{heat}}} \tag{7}$$

where E is the energy or exergy content of the electricity and heat outputs.

Table 10 shows the further allocation factors considered in this study, taking into account that heat is the coproduct of electricity production.

3 Results

The impacts were estimated for each phase according to the three methodologies, referred to the chosen functional unit. In this section, the results, summarized in Table 11, are presented.

Overall, the entire life cycle of the IPRP plant is responsible of 1,604,000 kg CO_2-eq of greenhouse gas emissions. The GWP of the IPRP plant, according to the substitution method, was evaluated equal to 0.14 kg of CO_2 per kWh produced. The utilization phase of the IPRP plant results as the most impactful among the life-cycle stages, as shown in Table 11. The contribution of the construction phase is lower

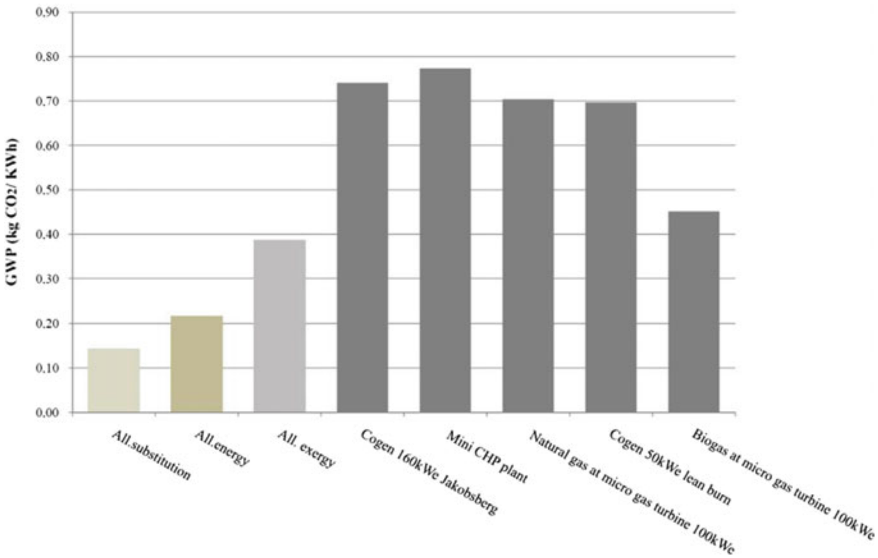

Fig. 6 IPCC method: comparison of GWP with other CHP plants

than 4% of total impact, while end of life phase is less than 1%, latter considering their absolute values.

Figure 5 shows the GWP values estimated for all the processes involved in the life cycle, per each kWh of electricity produced. The recovered heat permits to avoid about 0.34 kg of CO_2-eq per kWh of electricity produced.

According to energy allocation and exergy allocation, the impact of the IPRP plant was estimated about 0.21 and 0.39 kg of CO_2 per functional unit, respectively. Figure 6 shows the influence of the allocation procedure chosen on the results obtained with the methodology applied. In addition, Fig. 6 shows the comparison of GWP of the glycerol-derived syngas with other common combined heat and power (CHP) technologies.

4 Discussion

The impacts of the end of life of the IPRP plant were allocated to the disposal processes of the construction materials. It is worth noting that the use of recycled products permits to avoid the impacts associated with the production of the raw materials. In detail, recycled material allows to avoid 0.002 kg CO_2-eq per kWh per year.

According to the allocation exergy, the GWP values of the IPRP plant are half of the ones of the other common technologies, except the biogas plant. The GWP of the IPRP plant is 0.39 kg of CO_2-eq/kWh and it appears more advantageous with respect to other technologies, whose greenhouse gas emissions range from 0.45 to 0.75 kg of CO_2-eq per kWh, as shown in Fig. 6.

It is worth noting that the applied allocation factor is based on the exergy content of the electricity and the heat produced, considering also the losses due to irreversibility. Increasing the recovered heat from exhaust gases, the environmental profile of the IPRP plant will enhance.

On the other hand, considering the substitution allocation, the environmental profile of the IPRP plant appears the best technology solution with respect to the other ones.

Considering the substitution method, the influence of the credits is relevant, since the impacts result lower than the ones of the other CHP plants. The GWP of recovered heat is evaluated equal to −0.34 kg of CO_2-eq/kWh, where the negative values indicate the benefits due to the avoided impacts.

5 Conclusions

The aim of this paper is to evaluate the environmental impacts of the pyrolysis process of crude glycerol in a combined heat and power (CHP) plant based on the integrated pyrolysis regenerated plant (IPRP) technology.

The biomass-glycerol co-pyrolysis was analyzed by means of the LCA methodology; inventory data were derived from an existing pilot plant and referred to the functional unit of the system (kWh of electricity produced by the microturbine).

The analyzed system included the production of glycerol, the sawdust from sawmill processes, the production of glycerol and wood pellets, the pyrolysis process and the electricity, and heat cogeneration at the plant. The construction phase of the plant was included, as well as the decommissioning of the plant. The impacts were evaluated by IPCC method.

Since heat is recovered from exhaust gases for heating purposes and to dry biomass, a substitution allocation was applied, in order to consider the avoided impacts as credits respect to the total impact.

Results show that the use phase at the IPRP plant is the most impactful among the various life cycle stages. On the other hand, the recovered heat permits to avoid 0.34 kg of CO_2-eq per kWh produced.

Since the main product is electric energy and the heat is co-produced, the influence of the chosen allocation method was investigated, considering different allocation factors based on energy and exergy outputs.

It was observed that, increasing heat recovered from the exhaust gases, the environmental profile of the plant improves. The advantages of glycerol co-pyrolysis are noticeable comparing the results with the impacts of other common CHP technologies, fed with fossil fuels or biogas.

According to the allocation based on exergy outputs, the GWP value of the IPRP plant was about 50% lower than the impacts of the other technologies, with the exception of the biogas plant.

The environmental profile of the IPRP plant results the best solution with respect to the other ones.

Limitations of this study regard the lack of primary data for crude glycerol production. Using primary data, uncertainty in LCA study can be reduced. Further study will be addressed to estimate the uncertainties linked to the use of different types of data.

However, the results of this study can certainly extend the current databases about biofuels exploitation and can be a valid support for analysts interested in similar LCA studies in the same sector.

The exploitation of crude glycerol is capable to create interesting industrial links. In fact, the IPRP technology has low environmental impacts with the possibility to recover heat waste. For example, the technology is able to work with a combined gas and steam cycle. Moreover, this technology is suitable for recovering energy from biomass with low heating value, as agro-food residue, likewise corn, or from cardboard packaging.

Hence, private companies or agro-food industries and farmhouses, with high energy consumptions to break down, can be interested to convert residues in bioenergy. In addition, the valorization of crude glycerol by means of pyrolysis process noticeably reduces the costs of the biodiesel production. To further optimize the process, an IPRP plant fed by glycerol/biomass mixture may be also integrated into a biorefinery.

Further analysis could be addressed to investigate the effect of varying exergy factors on the LCA results, including the irreversibility loss in the calculation, but also how allocation factors affect the LCA results. Further research could be addressed to evaluate the influence of scaling-up of the plant.

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Decarbonisation of Electricity Generation: Efforts and Challenges

O. M. Babatunde, J. L. Munda and Y. Hamam

Abstract In satisfying the perpetually increasing energy demand, utility companies have traditionally depended on fossil-based energy sources (natural gas, oil and coal). These fuels are carbon-intensive, and burning them has negative implications on both human health and environment. However, in order to make sure that the global temperature rise is kept below 2 °C based on the Paris Agreement, it is essential that the electricity generation industry is subjected to transformation through the process of decarbonisation. Renewable energy sources have the tendency to mitigate the negative effects of the conventionally powered power plant. The move to renewable sources motivated the start of the process of decarbonisation—reducing the carbon intensity of the electricity generation. Furthermore, the adoption of demand-side management, carbon capture and storage, clean coal technologies, decommissioning of ageing fossil fuel-powered plants (replacing it with renewable energy-based plants), nuclear energy and adoption of stringent low-carbon policies can also aid decarbonisation of the power system sector. This work presents the trends and challenges in the decarbonisation of the power generation. This will help in achieving an all-encompassing strategy for the attainment of green economy. It is predicted that in order to maintain 2 °C temperature rise by 2050, the following technologies will contribute to emission reduction: carbon capture and storage 19%, fuel switching and efficiency 1%, hydro 3%, nuclear 13%, solar photovoltaic 9%, concentrated solar power 7%, wind onshore 9%, wind offshore 3%, biomass 4%, electricity saving 29% and other renewables 3%. It is clear that there is no singular approach that can entirely be used for the decarbonisation of the grid. An integrated approach

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S. S. Muthu (ed.), *Carbon Footprints*, Environmental Footprints and Eco-design
of Products and Processes, https://doi.org/10.1007/978-981-13-7912-3_3

that accommodates various policies and decarbonisation technologies will enhance low-carbon electricity generation.

Keywords Generation expansion planning · Power plant mix · Decarbonisation · Renewable energy · Emission reduction · Demand-side management · Climate change

1 Introduction

The ever-increasing thirst for electricity by human daily activities necessitates the need for periodic investments in new electricity facilities. In order to adequately and conveniently meet the ever-increasing energy demands, the power system industry is therefore categorised into distribution company (DISCO), transmission company (TRANSCO) and the generation company (GENCO). The GENCOs generate electric power which is sent through the transmission facilities owned by the TRANSCOs to the DISCOs. The DISCO is saddled with the responsibility of distributing electricity to consumers. The main objective of specifying the responsibilities of the different players involved in the electricity market is to efficiently and reliably satisfy the power demand based on various contradictory objectives (Sen and Bhattacharyya 2014).

To ascertain the reliability and sustainability of the electricity industry and forestall facility breakdown which may result in network collapse, it is essential to plan the generation, transmission as well as the distribution of electricity. Although the satisfaction on customer demands is very important, the sustainability of energy sources, as well as the environment, is also vital. Therefore, energy demands are supposed to be satisfied by reliable, environmentally friendly, and cost-effective power plants. Research efforts to arrive at a compromise between the components (reliability, sustainability and cost-effectiveness) result in a conflict among the subjects of engineering, management and economics.

The conflicting objectives that are derived from an attempt to plan the investments in the electricity industry result in an optimisation problem. In order to ensure that a particular generation expansion planning (GEP) investment is efficiently executed to satisfy the predicted load growth over a certain planning horizon (short, medium or long term), four fundamental questions need to be adequately answered. These include:

- *What*—the varieties of generator that should be included to the existing network.
- *How much*—the size of each new technology to be added.
- *Where*—the *location of the proposed generator*.
- *When*—the approximate time of addition along the planning horizon.

GEP is one of the most enthusiastically researched subjects by both decision-makers and the academics in the energy industry. It has been actively studied for about 70 years when it was first modelled as a linear programming optimisation problem whose only objective is the minimisation of the total cost invested in the generator (Masse and Gibrat 1957). The total cost functions usually include investment, fuel and operation costs over the whole planning horizon. This method for years has been used for centralised planning of the state-owned and regulated power system with strong monopoly on the generation, distribution and transmission networks. However, the deregulation of the electricity market, the introduction of new control strategies, global environmental challenges, inclusion of renewable energy and the attempt to accommodate uncertainties have led to a rapid change in the handling of the GEP. GEP is regarded as one of the most extensively discussed and complex topics in power systems. It has thus been presented by numerous studies in various optimisation dimensions. In a monopolised electricity environment, the objective of the operator is the minimisation of total cost, while the focal point in a deregulated electricity market is maximisation of profit. Thus, these emerging trends have introduced new constraints as well as objective functions which in turn have introduced more complexities in the representation and solution of GEP problems. These emerging trends make many of the new GEP models nonlinear, non-differentiable with high dimension and a combination of discrete and continuous variables.

From the aforementioned, in order to express the GEP close to what is practically obtainable, a large number of objectives and constraints will be needed, and as such, linear programming models may not be sufficient in representing such. To mitigate this challenge, many optimisation techniques/methods have been engaged for the formulation and solution of GEP optimisation problems. These include dynamic programming, mixed integer programming (You et al. 2016; Khodaei and Shahidehpour 2013), decomposition approach (Gorenstin et al. 1993; Tafreshi et al. 2012; Botterud and Korpås 2007; Fini et al. 2014) and nonlinear programming (Ramos 1989; Yakin and McFarland 1987). In a bid to decrease the complex mathematical nature of many of the GEP models and improve computational tractability, the aspects of flexibility are usually neglected (using specific assumptions) or parameters representing such are approximated.

Over the years, concerns about the sustainability of the conventional energy resource (energy security), the perpetual fluctuation in fuel prices, geopolitical changes, negative environmental impact of greenhouse gases (GHGs) emitted by fossil fuels have simulated research efforts into alternative energy resources. Thus, research efforts have been concentrated on the development and adoption of renewable energy sources for electric power generation globally. The technological advances in the two main intermittent RES (sun and wind) have particularly contributed to energy transition. Though capable of mitigating the emission of GHGs and ensuring resource sustainability, the inclusion of RES into the energy mix prompts other emerging issues such as efficiency, reliability and flexible power system network.

As earlier stated, past research efforts involving GEP have been concentrated on minimisation of the costs (Hamam et al. 1979; Sirikum and Techanitisawad 2006; Kothari and Kroese 2009). These include the investment cost, and operation and maintenance cost. More recently, due to environmental concerns, GEP investigations have extended to minimisation of emissions and the environmental impact of conventional generating units (Aghaei et al. 2013). To minimise emissions, various strategies have been proposed. These strategies include the implementation of renewable energy technologies (RETs) for the electricity generation, introduction of emissions penalties and adoption of DSM techniques. Due to the drop in the prices of PV and wind technologies, the use of RES for large-scale electricity generation has been proposed in generation expansion programmes (Aghaei et al. 2012; Rajesh et al. 2015, 2016a, b, 2017). If well planned and executed, RES can constitute a large share of the global energy mix by incorporating them across the entire planning horizon. In this regard, PPM models with renewable energy plants will be a better alternative. On the other hand, such RETs were mostly modelled without considering the fluctuations in their output. Meanwhile, the intermittent nature of RETs has received little attention in PPM models (Oree et al. 2017). The determination of such will help to determine the actual output of the renewable energy generating plants. Real-time determination of the output of renewable energy plants is therefore important. Other approaches in PPM have also adopted the integration of DSM techniques for the reduction of GHG emissions (Martins et al. 1996). According to Martins et al. (1996), when considered from a broader perspective, DSM is termed integrated resource planning (IRP). IRP involves the consideration of energy saving and load management as alternatives to perpetual generation expansion. Therefore, it is important to incorporate renewable energy plants, energy efficiency and storage units into the decarbonisation of GEP.

This work presents the trends and challenges in the decarbonisation of the power generation. This will help in achieving an all-encompassing strategy for the attainment of green economy.

2 Global Electricity Trends

The role of electricity in the development of the global economy is very crucial as its benefits are enormous and diverse. Electricity has great potentials in bringing about improvements in the living standards of people through increased productivity, improved levels of health care, improvement in education services and improvement in communication networks. Access to energy is an important need for human development, economic development and alleviation of poverty (Akinbulire et al. 2014). The quest for global access to electricity is an ongoing challenge affecting global development. The methods of electricity generation also have important impacts on the environment. The fossil-fired power plants (gas, coal and oil) have historically dominated the global energy mix. These methods of electricity generation have brought about increases in the emission of CO_2 and other GHGs which are fundamentally responsible for the recent global climate change (Babatunde et al. 2018a). A concerted transition in electricity sources is needed for global climate targets so as to avoid the negative impacts of climate change (Babatunde et al. 2018b).

There was approximately 3.1% (780 TWh) growth in electricity demand globally in 2017, while the global energy demand only increased by 2.1% in the same period. There was a strong correlation between the economic output of two emerging economies (China and India) and their electricity demand growth. With an economic growth of approximately 7%, China accounted for 48% of the electricity growth globally, while India with an economic growth of a little over 7% accounted for 180 TWh (approximately 23%) (International Energy Agency 2018a).

In total, China and India accounted for nearly 70% electricity demand globally in 2017, while 10% growth is attributed to other developing countries in Asia. Significant steps have been taken to improve access to electricity in many communities in India. The government has been able to extend access to electricity to about five hundred million individuals since the year 2000, thereby almost doubling the rate of access from 43% in the year 2000 to 82% of the present population (International Energy Agency 2018a). The developed countries were responsible for approximately 10% of the global electricity demand growth. The USA reduced its average electricity demand by 80 TWh in 2017. Furthermore, the European Union grew its electricity demand by 75 TWh in the same year. This is equivalent to the predicted economic growth of 2.3% in the same year. The demand for electricity in Japan also increased by about 15 TWh (International Energy Agency 2018a).

The global power plant mix (in terms of ratio) has remained relatively unchanged over the last century. The four key traditional electricity sources that have dominated electricity generation over the last 40 years include natural gas, large hydro, coal and nuclear. In 2017, renewable energy sources were responsible for approximately 50% of the cumulative global additional generation required to satisfy the rising electricity demand. With this addition, the renewable energy fraction in the global electricity mix rose to 25%—a record high. Figure 1 shows the global electricity mix for 2017. Coal accounted for 37%, renewables 25%, gas 23%, nuclear 10% and oil 4% (International Energy Agency 2018a).

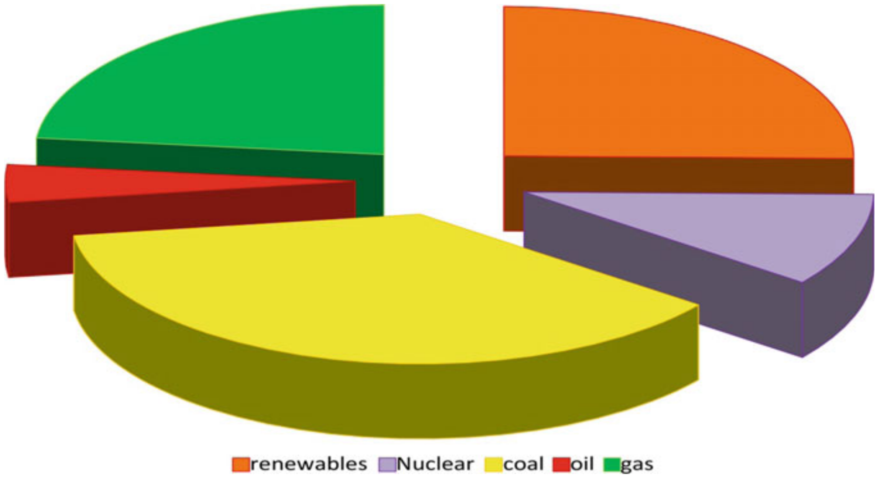

Fig. 1 2017 global electricity mix % (International Energy Agency 2018a)

3 Electricity and Greenhouse Gases

Electricity generation accounts for approximately 43% of worldwide CO_2 emission. Out of this value, coal-fired power plants contribute 70% by releasing 1.024 kg of CO_2 for every kWh of energy generated as compared to gas-fired power plants which emit 0.49 kg of CO_2 for every kWh. On the other hand, the only emissions attributed to RES such as wind, hydro, solar PV and concentrated solar power (CSP) are the ones emitted during their production. With regard to solar energy (PV and CSP), on average, between 7 and 45 g of CO_2 is emitted when one kWh of electricity is generated (Fig. 2). A wind turbine and a hydropower plant release about 16 and 6 g for every kWh, respectively (Société Française d'Energie Nucléaire 2017). For nuclear power plants, even after the future requirement to decommission old plants is included, the CO_2 emission stands at 15 g for every kWh of electricity generated. This is in sharp contrast when compared to the quantity attached to the coal-fired plants (1.024 kg). From the foregoing, it is evident that the CO_2 attributed to renewable energy sources is lower, and as such, the negative environmental impact will be lower when compared to that attributed to fossil-powered plants. Apart from this, fossil sources are exhaustible, while the renewable energy sources can be continuously harnessed. As such, renewable energy for GEP is now receiving research attention and huge investments. It is reported that in 2015, renewable energy received more than double the investment received by fossil-powered plants (coal and gas). Although nuclear electricity generation releases a small amount of CO_2 to the environment, its

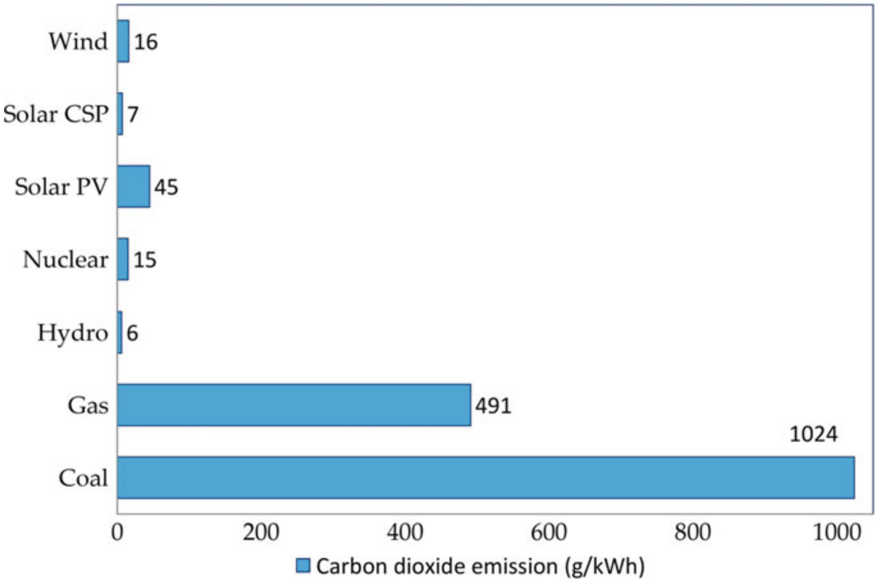

Fig. 2 CO_2 emission attributed to different generation technologies

adoption is receiving stiff opposition because of the danger of proliferation and the concerns of nuclear waste disposal and accidents. One of such accidents was the one that happened in Fukushima. Countries such as China, UK and France are investing in new-generation nuclear plants in a bid to cut emissions (Planete-Energies 2016).

4 Decarbonisation of the Power Industry

4.1 GEP, Environmental Issues and Climate Change

Some of the drivers of the decarbonisation of the generation expansion plans include the negative effects of greenhouse gases on the environment and human health, and the most prominent is the issues surrounding global warming and climate change. As such, various eco-friendly regulations, affecting generation expansion planning programmes, are legislated and adopted as sustainable development policies at both national and international stages. For example, in the 1990s, the federal government of the USA presented a Clean Air Act Amendments which was expected to force utility companies and energy planners to embrace strategies that would reduce the amount of emissions from fossil fuel-fired power plants (Abdollahi et al. 2012). Furthermore, the Kyoto Protocol was globally ratified by many countries for the mitigation of GHG emissions from every sector including the power industry (Protocol 1997). Subsequently, various strategies and constraints that limit GHG emissions from the electricity industry have been put in place. Some of these strategies include DSM and renewable energy technologies.

4.2 Environmental Considerations in GEP Studies

In order to handle the environmental impacts of emissions from GEP, many early studies imposed constraints on the maximum limit of permissible emissions from the generators. Some other methods incorporated the external costs related to the negative environmental effects of power generation by the different generators in the network.

For instance, a GEP model that dealt with the minimisation of investment cost, operation and maintenance cost, generation costs and CO_2 emission-related costs has been presented (Chen et al. 2010). In the face of increasing green environment awareness programme, Mejia-Giraldo et al. proposed a GEP model which embedded the following environmental policies: introduction of CO_2 emissions tax, reduction of annual emission rate and the gradual removal of inefficient generators from the system (Giraldo et al. 2010). Owing to the inclusion of various environmental constraints in the model, the proposed GEP optimisation model selected fewer capacities of the fossil-fuelled power generators due to the emission of pollutants.

The integrated GEP model accommodates the influence of different low-carbon features in its constraints. These constraints are associated with low-carbon technologies, emission trading mechanisms and CO_2 emission reduction targets. The decision variables include CO_2 allowance trading, low-carbon technologies implementation and carbon capture and storage retrofit on conventional generators. The model's objective functions include maximisation of income from CO_2 trading mechanism, CO_2 reduction costs and emission penalty. Furthermore, a GEP model that incorporated two environmental impact-related constraints (air pollutant emission and concentration) was proposed by Sirikum and Techanitisawad (Sirikum and Techanitisawad 2006). In order to make the model robust, the authors also included demand-side management investment cost and environmental cost expected from the damage cost of emissions of thermal plants into the objective function. A GA-based solution technique which breaks the GEP model into two portions was adopted. The GA provides a solution for the combinatorial part (generation mix), and based on these solutions, continuous variables that minimise the total cost subject to the listed constraints are determined using LP. For validation purposes, the Thailand power system was used as a case study. In order to present an energy plan for Apulia region in southern Italy, Cormio et al. presented a linear GEP optimisation model whose technique is based on energy flow analysis (EFA) (Cormio et al. 2003). The model is aimed at reducing both cost and the environmental impact. The EFA presented a detailed analysis of the basic energy sources utilisation which comprised process by-products, biomass, emissions, power and heat generation, solid wastes and end-use sectors. The objective function of the proposed GEP model minimises the total system cost. Some of the constraints considered in the study include construction time, limits on electrical energy generation, plant/facility operation limits, electricity generation and consumption balancing, peak demand satisfaction and limits on renewable energy potentials. The model is verified based on two case studies. The results from the simulation show that combined cycle power plants can contribute more in terms of renewable energy penetration as compared to any industrial cogeneration, biomass, waste to energy and wind power.

4.3 Emission Reduction Handling in GEP

In order to handle the issue of emission reduction in GEP, many studies have defined it either in the objective function (minimisation of its quantity or associated cost) or in the form of constraints by placing limits on the amount of emission expected from the fossil-fuelled power plants. Diverse mathematical techniques have been proposed for estimating the quantities of pollutants generated by various fossil-powered power generators. These include the quadratic model, the quadratic polynomial model, a hybrid polynomial and exponential emission function, linear model and emission coefficients method (Table 1) (Sadeghi et al. 2017). A review of GEP literature shows that the issue of emission reduction has received outstanding attention (Meza et al. 2007, 2009; Unsihuay-Vila et al. 2011; Tekiner et al. 2010; Jadid and Alizadeh 2011;

Table 1 Emission consideration in GEP (Sadeghi et al. 2017)

Type of emission model	Mode of consideration		
	Constraints	Objective	
		Emission quantity	Emission cost
Combined	Kannan et al. (2007), Hariyanto et al. (2009), Jadidoleslam and Ebrahimi (2015) and Hemmati et al. (2016)	–	–
Linear	–	–	Khodaei and Shahidehpour (2013)
Emission coefficient	Park et al. (1998), Tekiner et al. (2010), Jadid (2011), Min and Chung (2013), Surendra and Thukaram (2013), Zhang et al. (2013b), Ghaderi et al. (2014) and Sadeghi et al. (2015)	Martins et al. (1996), Shahidehpour and Kamalinia (2010), Hasani-Marzooni and Hosseini (2011), Unsihuay-Vila et al. (2011), Tekiner-Mogulkoc et al. (2012), Zhang et al. (2012) and Mavalizadeh and Ahmadi (2014)	Sherali and Staschus (1985) and Kaymaz et al. (2007)

Khodaei et al. 2012; Tekiner-mogulkoc et al. 2012; Rouhani et al. 2014; Javadi et al. 2013; Khodaei and Shahidehpour 2013; Aghaei et al. 2014; Palmintier and Webster 2011).

4.3.1 Power Plant Decommissioning

Electricity is a commodity that must be used as soon as it is produced because large-scale storage is not economical in many cases. Furthermore, the society is perpetually thirsty for electricity for the running of daily activities which are vital to human existence. Due to these facts, generating plants on the grid usually run uninterruptedly for many hours annually. Many of the generators are already old and sometimes inefficient due to ageing, while new ones with additional appropriate technological features are being incorporated into the grid. Conversely, environmental policies, regulations and targets fixed by various organisations, governments and establishments have enhanced the motive behind the decommissioning of fossil-fuelled generating facilities (especially coal and heavy oil) (Hillman and Zhang 2012). In the long-term power plant expansion planning, the timing for the removal of old and inefficient generating units usually has a major effect on the schedule of newly commissioned facilities.

In order to obtain a robust model that accounts for plant retirement (most especially conventional units), it is important to include power plant decommissioning decision variable into a GEP model. Apart from the reduction of emission rate, the decision to retire a particular unit is based on factors such as low reliability, high maintenance and operation costs caused by inefficiency of the units, and salvage value. Although the decommissioning of fossil fuel units (and replacing it with renewable energy plants) can encourage a transition from a grossly carbon-reliant energy generation to a low-carbon energy generation, it presents a major challenge for both government and utility companies across the globe. The variability of these low-carbon sources, as well as the cost of retrofitting, is a major barrier. This is evident in the review of previous studies which shows that the inclusion of power plant unit decommissioning in GEP optimisation problems has received limited attention (Tohidi et al. 2013; Min and Subramaniam 2002).

4.3.2 Demand-Side Management (DSM) Practices

Having learnt from the energy crisis that happened in the 1970s, electricity utility companies in the USA initiated the implementation of demand-side management (DSM) practices. DSM practices were effected in response to the persistent and continuous natural gas and petroleum price upsurge as well as the anticipated shortages (Loughran and Kulick 2004). The DSM programmes were implemented with the aim of modifying customer's electricity demand through several techniques comprising of attitudinal changes through enlightenment and financial motivations. Rather than investing in the installation of more generating units to satisfy the ever-increasing appetite of energy-thirsty customers, DSM practices through various incentives encourage consumers to reduce or delay electricity consumption (Babatunde et al. 2018a). Conventionally, DSM is perceived as a tool for the reduction of peak load so that electricity companies (GENCO, TRANSCO and DISCO) can defer the addition of new capacities (Babatunde et al. 2018a). This consequently defers the potential high investments involved in enhancing the power system network to accommodate increased power demand. The reduction of overall electricity demand from the electricity grid through DSM increases the reliability of the system by reducing the frequency of blackouts, brown-outs and other electrical emergencies. Since additional capacities (e.g. power plants) are delayed, electricity prices are reduced, the reliance on expensive imports of fuel is reduced, and reduction in GHG emissions to the environment is ensured. Therefore, the application of DSM in the power system sector offers substantial economic savings, technical benefits (increased reliability) and environmental advantages (reduction of emissions).

Drivers of Demand-Side Management

Various reasons have been attributed for the promotion of the adoption of DSM by utilities. Some of the drivers put forward include cost reduction in operation and maintenance of facilities, improved reliability, improved market as well as enhanced environmental and social improvement (Babatunde et al. 2018c). Ordinarily, promoting increased energy consumption so as to increase sales on the part of the utility will seem like a profitable idea; however, this will only work when there is excess capacity and the only factor that determines profitability is revenues. Conversely, direct proportional relationship between increased revenue and higher profitability does not always exist. According to a report "in some situations, a least-cost planning approach could prove that the implementation of DSM measures is more profitable than investing in new generating capacity" (UNIDO 2010). As a result, electricity companies would rather advise and promote DSM and energy efficiency techniques among their consumers. From the social and environmental standpoint, a reduction in electricity demand due to the adoption of energy-efficient practices reduces the environmental effect of electricity generation (from fossil-fuelled power plants) and consumption. This would project the image of the utility companies involved. DSM can be broadly categorised as demand response or energy efficiency. In terms of the period of application and impact, DSM can be categorised as energy efficiency, time of use (TOU), spinning reserve, market demand response and physical demand response (Koltsaklis and Dagoumas 2018) (Fig. 3). The TOU instantaneously ties the energy tariff to the energy cost. TOU penalises some period of energy use with a higher tariff in order to compel consumers to minimise energy consumption. In TOU scheme, lower tariff usually applies during off-peaks and partial peaks period, while at peak periods, the tariff is higher. This usually modifies the consumption pattern of the consumers by moving energy use away from peak periods which is usually more expensive. With this method, the customers save costs of purchasing electricity, while in the part of the utility, the fatigue on the grid is avoided.

4.3.3 Inclusion of Energy Efficiency Techniques in GEP

Energy efficiency techniques comprise of strategies and efforts that cause permanent changes/reduction in the size of the energy demand from the consumers' side of the electricity market. The changes are usually caused by the modification on the features of the connected equipment to enhance (reduce) its energy consumption pattern. The EETs when adopted to reduce energy consumption must not distort the comfort level enjoyed by the end-use consumers (Goldman et al. 2010). EETs modify energy consumption through the use of energy-efficient equipment and gargets. The use of such gargets ensures that less energy is consumed to perform their normal tasks and attain the same level of satisfaction.

EETs are also regarded as energy source (just like natural gas, coal, RES and nuclear) and therefore considered as virtual generators whose negawatt power can be used to satisfy energy demands (Hu et al. 2010). The effects of EETs are instantaneous and stable with long-term energy and emission savings (Koltsaklis and Dagoumas 2018). They are therefore regarded as the most effective DSM method (Palensky and Dietrich 2011). As a decarbonisation mechanism, EETs through the reduction in energy consumption will reduce the energy consumption as well as the emission

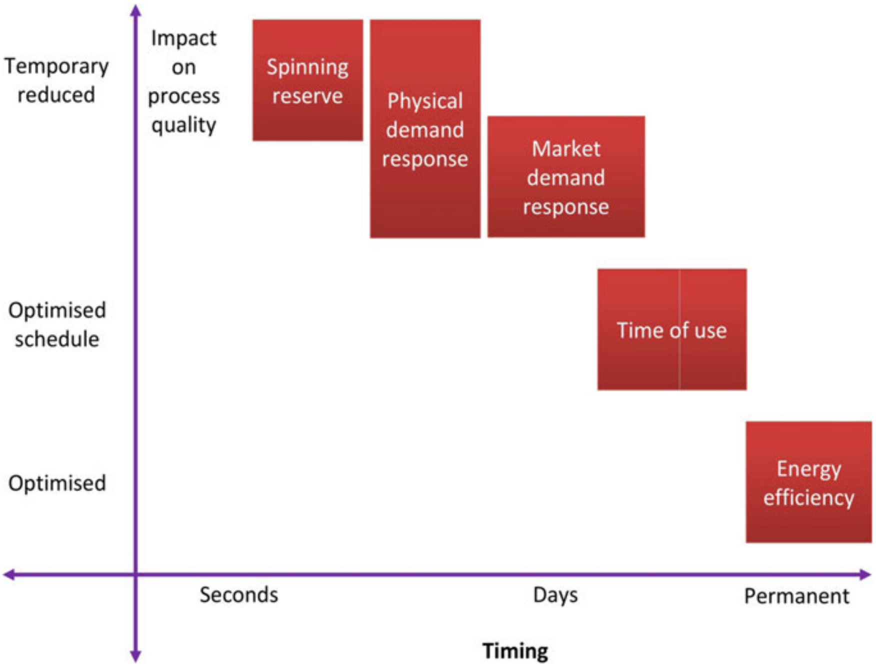

Fig. 3 Categories of DSM (Palensky and Dietrich 2011)

level from fossil-powered generators. When applied on both domestic and industrial loads, the cumulative energy saving can mitigate GHG emissions to a large extent. In 2016, it was reported that through the use of EETs, a cumulative energy savings of about 12%, was achieved since its adoption in the year 2000 (IEA 2017). In an attempt to capture the influence of energy efficiency on generation expansion planning, Ghaderi et al. presented a GEP model in which energy efficiency resources were modelled as efficiency power plant (Ghaderi et al. 2014). To ensure that investors at every stage of the planning obtain maximum profit, the GEP problem was modelled as a two-level optimisation problem. The lower-level problem was modelled to maximise the social welfare, while the upper-level problem ensures profit maximisation. Limmeechokchai and Chungpaibulpatana also presented and integrated GEP model which evaluated the emission reduction and the economic effectiveness of adopting cool storage air-conditioning (CSA) in a commercial sector (Limmeechokchai and Chungpaibulpatana 2001). Simulation results showed that the installation of CSA has the potential to defer the installation of approximately 1000 MW of fossil-powered plant between 2010 and 2011. In another study by Montie et al. (Motie et al. 2016), grid-connected electric cars and wind resource were considered as a technique for achieving energy efficiency goals in GEP. Other studies that included EETs from emission reduction in GEP include Unsihuay-Vila et al. (2011) and Fan et al. (2015). From the reviewed literature, the implementation of EETs results in energy and cost savings, deferment of capacity expansion, minimisation of negative environmental impact. Furthermore, the time of implementation and cost of implementing EETs are generally lower as compared to investing in new capacities to satisfy energy demands.

4.3.4 Demand Response Programmes and GEP

Demand responses are the adjustments in energy consumption made by the demand side of the electricity network. Consumers make modification to their "business-as-usual" consumption pattern in response to variation in energy prices over a period of time or to incentives. These incentives are proposed to ensure reduction in energy consumption at times of high system's market prices or when the reliability of grid is threatened. DR can be categorised along two major dimensions, namely: initiation criteria and motivation dimension (Rocky Mountain Institute 2016) (Fig. 4). The initiation dimension indicates how and when the utilities contact the programme participants to curtail demand, while the motivation dimension indicates how the utilities encourage the programme participants to adopt DR. From Fig. 4, it could be seen that DR could be activated either based on the emergency/reliability related issues or for economic reasons. While the aim of the DRPs is to modify the shape

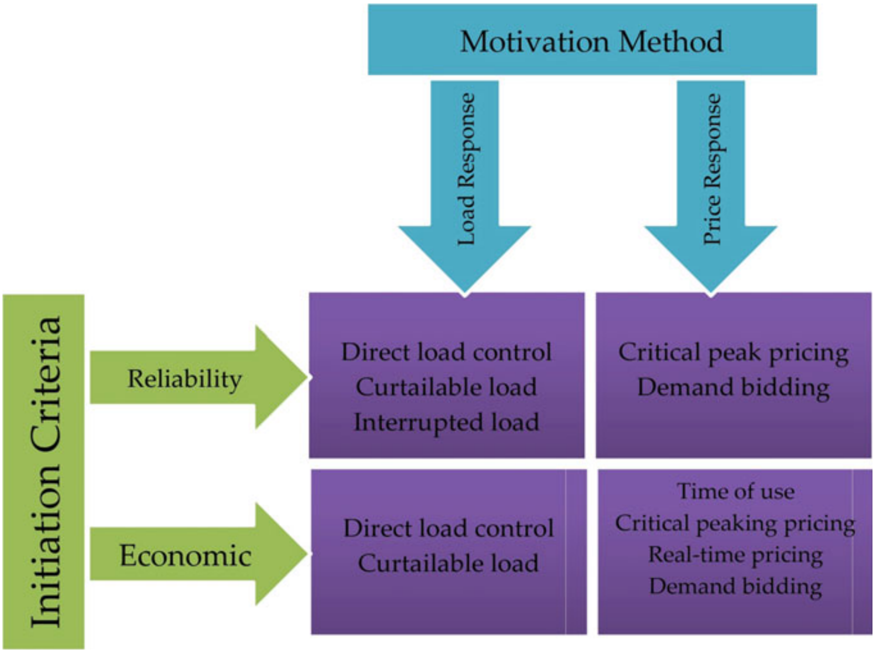

Fig. 4 Classification of demand response programmes based on initiation criteria and motivation method (Rocky Mountain Institute 2016)

of the demand, the EETs adjust the load level. A study which investigates the state-of-the-art systematic frameworks for adopting DRs in energy planning has been presented (Satchwell and Hledik 2014). Using dynamic programming, Sheikhi et al. modelled the stochastic nature of both DGs and DRs and the impact of DRPs on energy resource expansion planning in a deregulated environment (Fini et al. 2013). The outcome of the study indicates that adopting DRP in GEP has the tendency to increase the penetration of renewable resource in the energy mix via efficient demand control mechanism for smoothing the variability of RES-based units during normal grid conditions and by avoiding price spikes during critical grid conditions.

4.3.5 GEP and Carbon Capture Storage

Another possible alternative for the abatement GHG is CCS. Substantial research efforts have been directed at CCS because it can offer a cost-effective and smooth migration to a less carbon-intensive power generation mix in the next few decades. In order to make this a reality, appropriate guiding frameworks and policies for geologically sequestrating the CO_2 have been proposed. Based on these frameworks, many studies and large-scale projects have been launched to develop and improve CCS technologies worldwide (IPCC 2007). Basically, the alternative of capturing and storing CO_2 affords the prospect of allowing huge reserves of fossil fuels to be exploited and consequently being able to control GHG emissions during expansion planning. In this regard, studies that consider the impact of CCS on GEP strategies are beginning to spring up (Nguyen 2008; Chen et al. 2010; Bakirtzis et al. 2012; van den Broek et al. 2008; Chunark et al. 2014; Zhang et al. 2013a; Unsihuay-Vila et al. 2011; Saboori and Hemmati 2016). The outcome of various studies conducted on the impact of CCS on GEP has indicated that the conversion of the conventional coal-fired plants to low-carbon-intensive alternatives combined with CCS can have a positive effect on the total investment cost, operation and maintenance costs and the emission costs. The global growth of CCS is slow due to the high cost of investments and the lack of financial and political will by various governments (World Nuclear Association 2018). In 2016, it is reported that there were only 17 large-scale CCS projects functional worldwide (World Nuclear Association 2018).

4.3.6 GEP and Clean Coal Technologies

Worldwide, coal currently has the largest share of the global electricity mix. It is responsible for nearly 37% of the global electricity production in 2017, and this dominance is expected to continue in many countries for years to come (International Energy Agency 2018b). Other fossil fuel resources account for a combined percentage of 27% (gas—4%, oil—23%). Out of the three fossil fuel sources, coal emits more air pollutants (Sadeghi et al. 2017). The use of inefficient coal generation units increases these contaminants because of inefficient combustion. As these conventional coal-fired units approach their retirement period, they are expected to be replaced with units with no or lower carbon emission capabilities. One of such technologies is the clean coal technology. According to World Nuclear Association, "clean coal is a term gradually being used to refer to supercritical coal-fired plants without CCS, on the basis that CO_2 emissions are less for older plants, but are still much greater for nuclear or renewables" (World Nuclear Association 2018). These technologies often operate at around 42–48% thermal efficiency (World Nuclear Association 2018). Some of these technologies include supercritical and ultra-supercritical pulverised coal combustion, circulating fluidised bed combustion and integrated gasification combined cycles (Chen and Xu 2010). Out of the CCTs mentioned, it is reported that ultra-supercritical pulverised coal combustion and integrated gasification combined cycles have better potentials of future utilisation (Franco and Diaz 2009). At present, CCTs are mainly used as retrofit for medium and small size coal-fired units in countries like Spain and China (National Development and Reform Commission (NDRC) 2007; Delgado et al. 2011). Delgado et al. evaluated the impact of CCTs on GEP-related emissions. The studies recommend that concurrent integration of nuclear and CCTs units is incompatible (Delgado et al. 2009, 2011). Based on the two studies, Sadeghi et al. concluded that "high investment costs from one hand, and low emission and fossil fuels costs of nuclear units from the other hand can result in discarding them" (Sadeghi et al. 2017). In another study, Tanoto and Wijaya investigated the environmental and economic perspective of adopting CCTs in a long-term GEP problem (Tanoto and Wijaya 2011). The study concluded that in order to attain low-carbon generation mix in the future, incentives and policies that support the technologies are inevitable.

4.3.7 Nuclear Power in GEP Studies

The nuclear-fuelled power generator is CO_2 free and has the potentials to mitigate the rise in GHG if it can replace the base-load fossil-powered sources. Nuclear powered plants are one of the major generation alternatives with various advantages which include cheap fuel, compact waste, and ability to serve base loads. However, there are some drawbacks of nuclear power generation option as presented in Table 2. Being one of the leading conventional power generation alternatives, nuclear generators have been included and considered in GEP models with only few of them including its emission-free features (Nakawiro et al. 2008; Careri et al. 2011b; Habib and Chungpaibulpatana 2014; Meza et al. 2007, 2009; Vithayasrichareon and MacGill 2012; Unsihuay-Vila et al. 2011; Delgado et al. 2009; Unsihuay-Vila et al. 2010; Delgado et al. 2011; van den Broek et al. 2008; Tekiner-Mogulkoc et al. 2012; Chunark et al. 2014; Pereira and Saraiva 2013; Zhang et al. 2013a; Gitizadeh et al. 2013; Palmintier and Webster 2011). In many GEP studies, the threats related to the use and daily operation of nuclear power plants are given little research attention. In order to ensure the safe operation of these units, it is essential for the planning process (and model) to include factors that account for radioactive waste conveyance, waste removal, proliferation and level of reactor safety. It is therefore important that GEP with nuclear units considers and guarantees nuclear and radiological safety to the public and environment. Including these factors will ensure that the effects of nuclear power plant accidents that were experienced in Ukraine (Chernobyl) 1986, Argentina (Buenos Aires) 1983 and Japan (Fukushima) 2011 are either avoided or minimised (Sadeghi et al. 2017). Based on the experience of the Fukushima nuclear accident, Zhang et al. (2012) conducted a GEP study to analyse the economic and environmental implication of various nuclear case studies. The study shows that the total removal of nuclear power plants from Japan's 2030 power plant mix may result in a major increase in the cost of power production and GHGs. This will also increase the dependency on exportation of natural gas and coal which will in turn increase uncertainty in the generation expansion plan. The study also reported that only a fraction of the present load served by the nuclear units can be replaced by the renewable energy and natural gas-powered units. In a similar study, the effect of Korea's nuclear expansion policy on GEP was evaluated (Min and Chung 2013). Just like the Japan case, it costs more to replace some of the nuclear units with other energy alternatives. The paper, however, emphasised the need for the Korean energy mix to reduce its reliance on nuclear energy because of undermined social receptivity from the Fukushima disaster. The impact of eco-friendly constraints from hazards and risks related to nuclear power plants on GEP has also been explored (Zhang et al. 2013b; Santos et al. 2013; Kim and Ahu 1993). A summary of studies on emission reduction mechanisms is given in Table 3.

4.4 GEP and Intermittent Renewable Energy

One of the major drivers of green economy in the last decade is the renewable energy resources. This is due to favourable factors such as reduction in costs of RE technologies, technological innovations and developments of sustainable policies. Apart from its tendency to reduce GHG emission from electricity generation, RE sources can also guarantee future energy security, thereby ensuring sustainability. Based on these benefits and strict emission curtailment policies, many countries are now embracing the adoption of renewable energy for electricity generation. This is expected to increase the renewable energy share in the worldwide power plant mix. It is expected that by 2050, the renewable energy share will rise to 57% of the total demand served (International Energy Agency 2012). To achieve this, intermittent renewable energy sources (majorly solar and wind) are presently being explored and expected to take a major share of the renewable energy contributions. Some of the policies that have been proposed and adopted to ensure the increased penetration of renewable energy power generation include feed-in-tariff mechanism, quota obligations system combined with tradable green certificate, auction and tendering scheme, emission trading system (ETS) and carbon tax

For the main part of the last century, the major source of electricity generation is fossil fuel-powered plants. These technologies are flexible and can be easily varied to match the demand side by adjusting the fuel inputs. Conversely, including renewable energies into the power plant mix may lead to instability of the grid system because

Table 2 Comparison of energy sources considered in GEP studies (The Virtual Nuclear Tourist 2019)

Source	Benefits	Drawbacks
Hydroelectric	• Operation is inexpensive • Used for base-load and peak filling	• Construction is very expensive • Water resource depends on meteorological factors which increase uncertainty • Depends on the availability of water resource (variable source) • Collapse of dam may lead to loss of property and lives • Negative effects on aquatic life • Flooding can occur at downstream
Wind	• Wind is freely accessible when available • Can be deployed for water pumping for rural communities and on farms • Technology is fast developing and cheap	• Requires 3 times the quantity of installed capacity to satisfy demand • Geographical limitation of wind resource • May require expensive energy storage • Resource is intermittent in nature • Wind turbine tower can endanger birds and their natural habitat • May cause whale beaching
Biomass	• Industry is emerging • Job creation • Can aid rural electrification • Can be useful for home heating	• If small plants are used, it can be inefficient • It can be a major cause and contributor to GHGs if the plant is not well designed
Solar	• Solar radiation is free	• Intermittent in nature and geographically specific • Requires vast space of land for large-scale generation • Expensive • Sunlight depends on the time of the day (for any location)
Nuclear	• Fuel is not expensive • Concentrated source of energy generation • Compact waste • Well-developed technology • Easy to transport as new fuel • No GHG during energy generation • Used as firm capacity	• Investment cost can be high in order to accommodate adulteration management, waste control, storages systems and disaster management • Nuclear proliferation • Accidents and sabotage can lead to major releases of radioactive elements that can lead to health hazards (a case of Fukushima and Chernobyl)

(continued)

Table 2 (continued)

Source	Benefits	Drawbacks
Oil/gas	• Easy to obtain • Better as space heating energy source	• Not available in every location • Reliance on it causes energy dependency • Political crisis can cause shortages and high purchase prices • By-products of combustion cause releases of GHGs
Coal	• Cheap • Used as firm capacity	• Expensive pollution control mechanisms • Major cause of GHGs and acid rain • Movement of coals to power station is expensive • By-products (fly ash) contain heavy metals that are harmful to the environment • Deaths have been reported during the mining of coal

Table 3 Studies on emission reduction mechanisms

Emission reduction mechanism	References
Power plant decommissioning	Hoffman and Jeynes (1962), Tohidi et al. (2013) and Mavalizadeh et al. (2017, 2018)
Energy efficiency techniques	Gjengedal (1996), Martins et al. (1996), Limmeechokchai and Chungpaibulpatana (2001), Goldman et al. (2010) and Unsihuay-Vila et al. (2011)
Demand response	Pan and Rahman (1998), Antunes et al. (2004), Ghaderi et al. (2014), Monyei and Adewumi (2017) and Monyei et al. (2018)
Carbon capture storage	Nguyen (2008), Unsihuay-Vila et al. (2011), Bakirtzis et al. (2012), Fini et al. (2013), Zhang et al. (2013b), Satchwell and Hledik (2014), Guerra et al. (2016) and Saboori and Hemmati (2016)
Clean coal technologies	Franco and Diaz (2009) and Chen and Xu (2010)
Nuclear power generation	David and Rong-da (1989), Meza et al. (2007), Shahidehpour and Kamalinia (2010), Tekiner et al. (2010), Careri et al. (2011a, b), Delgado et al. (2011), Hasani-Marzooni and Hosseini (2011), Palmintier and Webster (2011), Unsihuay-Vila et al. (2011), Zhang et al. (2013b) and Sadeghi et al. (2015)

of the variability that comes with it. Intermittent energy sources are characterised most times by unanticipated fluctuations that cannot be controlled by the GENCOs. According to Oree et al. (2017), these variations can be recurrent if associated with daily and annual cycles (Oree et al. 2017) which cannot be linked to historical data. Though it mitigates emissions, the integration of renewable energy sources into the power system network introduces uncertainties in power system planning. As such, there arise the challenges of adequately matching the supply and demand. Furthermore, ensuring adequacy of installed spin reserves to satisfy the peak demand becomes a complex issue. At lower renewable energy penetration, flexibility is not a challenge because the grid is able to cancel out the fluctuations (Oree et al. 2017). However, when the penetration of renewable energy is very high in the power system network during GEP, the subjects of adequacy and operational flexibility become vital. Flexibility ensures that the grid promptly adjusts itself to match forecast and unforeseen variations in net electricity demand. The use of energy storage has the tendency to handle the issues of flexibilities caused by intermittent energy in the power system network. The most common energy storage used in GEP is the pumped hydrosystem. Water is pumped during the period when electricity is cheap and used for electricity generation when flexibility is needed.

5 Green Policies for Power Generation Decarbonisation

The climate change is a threat to human existence and needs immediate attention. As its contribution to the mitigation of climate change, the international community has enacted and adopted several conventions that have motivated many countries around the world to be totally engaged and prepared to consciously reduce their emission level. As a result, many countries have developed and adopted various energy policy frameworks (country-specific) geared at mitigating climate change and achieving a green economy. In this regard, the use of renewable energy sources is a fundamental and common policy for attaining sustainable development and reduction of climate change. There have been tremendous successes in many developed economies, but renewable energy penetration in developing economies is still hampered by economic and systematic factors. To ensure an increase of renewable energy share in the global power plant mix and make them competitive with the conventional sources of power generation, it is essential that both developed and developing economies adopt country-specific schemes that can enhance renewable energy. Some countries have therefore implemented favourable schemes that will encourage GENCOs to invest in the decarbonisation of the generating units. These schemes are in forms of subsidies which support the sustainability of green energy generation in order to compete with other sources of electricity generation to limit emission, climate change and dependency on fossil fuels. According to Sadeghi et al. (2017) “investments in renewable energy sources are either encouraged indirectly through efforts to mitigate power sector emission or by direct support schemes”. Some of the schemes adopted for emission mitigation and RES generation include feed-in-tariff mechanism, quota obligations system combined with tradable green certificate, auction and tendering scheme, emission trading system (ETS) and carbon tax (Sadeghi et al. 2017).

5.1 Carbon Tax

It has been established that the major cause of climate change is the emission of GHGs. Interestingly, electricity generation contributes about 42.5% of the CO_2 emitted annually. These gases are released during the combustion of fossil fuels used in electricity generation and are related to the carbon content of the fuels. In order to mitigate the indiscriminate release of these gases, carbon tax has been proposed. Carbon tax is a form of carbon pricing (in form of levy) imposed on the carbon content of fossil fuels. It is a mechanism proposed and used for the reduction and eventual elimination of carbon-based fuels whose combustion contributes to climate change. This taxation scheme ensures that users of fossil fuel pay for the damages caused on the environment through the release of CO_2 to the atmosphere. If appropriately formulated, it is a robust tool that can ensure the gradual migration from fossil fuel-powered electricity generation to green electricity production. The tax can be imposed at any point in the product life cycle of the fuel (Metz et al. 2001). Carbon tax can offer socioeconomic benefits such as increased revenue and mitigation of GHGs which consequently reduce the negative impacts these gases have on the environment and human health (Congressional Budget Office 2013). A school of thought has expressed concerns that carbon tax may lead to relocation of firms which may finally lead to workers losing their jobs (Rosewicz 1990). However, on the contrary, proper implementation ensures that emissions are efficiently reduced and provision of more jobs (Hoel 1998). Various studies have been conducted on the inclusion of carbon taxes in GEP (Careri et al. 2011a; Fini et al. 2014; Hu et al. 2010; Krukanont and Tezuka 2007; He et al. 2012; Nguyen 2007, 2008; Santisirisomboon et al. 2001; Gitizadeh et al. 2013).

5.2 GEP and FIT System

Feed-in tariff is a monetary incentive proposed to encourage dynamic investment in the use of renewable energy sources for the generation of energy (especially electricity). Usually, FIT uses long-term contracts and pricing related to the cost of electricity production from renewable energy. By proposing long-term agreements and guaranteed pricing, renewable energy producers are protected from the various risks associated with the generation of electricity through RES. FIT also ensures diversity in power plant mix. FITs are applicable to everyone that generates electricity through RES. FITs have three major features: (1) producers are remunerated based on the resources expended on energy generation; (2) producers are guaranteed access to the grid and (3) long-term agreement for electricity purchase (typically between

15 and 25 years) (KENTON 2018). As regards the major features of FIT, guaranteed investments and long-term contracts for RES-based technologies are the benefits from a decision-maker's perspective during capacity planning. Conversely, the possibilities of over-/underfunding related to the challenges in the estimation of future costs of generating electricity from renewable energy are the major concerns of regulators. The impact of FIT on GEP models has been presented by some studies (Alishahi et al. 2011; Li and Ren 2017; Fini et al. 2013, 2014; Ghaderi et al. 2014a; Sadeghi et al. 2015; Caramanis et al. 1982; Gitizadeh et al. 2013). Results of the majority of these studies show that FIT significantly increases the renewable energy share of the future power plant mix.

As regards capacity planning, a study which proposes a two-level optimisation technique for the design of efficient and effective incentive policies to motivate increased investments in renewable energy for GEP has been presented (Zhou et al. 2011). Sadeghi et al. in their study investigated the influence of FIT schemes on the social welfare for a hybrid renewable-conventional GEP framework. In the study, consumers are considered for patronising the financial burden of FIT (Sadeghi et al. 2015). Using a gravitational search algorithm, the authors presented a GEP model which determines the benefit gained by GENCOs and consumers. Numerical results elucidate the benefits (especially social welfare) of implementing FIT schemes in the GEP. Another study has also presented the impact of system planning on the social welfare based on the adoption of FIT in Ontario. Results of the study show that if FIT is not controlled, they have the tendency of precipitating large negative effects on costumers' social welfare. It is further stated that these adverse effects could be minimised by regulating its magnitudes (Pirnia et al. 2011).

5.3 Emission Trading

Also referred to as "cap and trade" and "allowance trading", emission trading is a GHG emission control mechanism which is market-based. This mechanism achieves emission control through the provision of financial incentives (Stavins 2003). Emission trading schemes have two major features, namely (a) setting a maximum limit or cap and (b) allowances that can be traded (equivalent to the maximum that certified allowance holders can emit). The limit ensures environmental sustainability, while the tradable allowance ensures flexibility for emissions sources to establish a convenient compliance framework. As such, emission trading allows defaulting establishments to choose the best way to achieve and meet the green policy targets. In emission trading, relevant government establishment/agency appropriates and vends a limited number of permits for the emission of specific amount of GHGs for a certain period of time. Companies whose activities lead to emission are mandated to possess a permit that is equivalent to their emission level. Companies that wish to increase their emissions are required to purchase from others with emission allowance and are ready to sell to them (Jaffe et al. 2009; Tietenberg 2003; Stavins 2003). Emission trading has been reported to be the backbone behind the climate change policy within the European Union (European Commission 2014). It has ensured reduction of EU's GHG emission by setting a cap on the maximum limit on emissions for the covered sector (European Commission 2014).

5.4 Auctions and Tendering Schemes

Tendering and auction schemes can also be used as a price-based incentive to encourage investments in renewable energy-based power generation (Careri et al. 2011a). They are viable tools used for the allocation of financial sustenance to RES schemes, based on the cost of electricity production. Through these schemes, the appropriate public authorities are saddled with the responsibilities of tender preparations. The lowest bidders are invited for power purchase agreements until all the allocated quotas have been bought. The bidding process for RES-based electricity is typically in form of a reverse multi-unit auction with offers for multiple units of RES capacity in MW or MWh or for specific RES projects submitted by various sellers to a single buyer. The sole buyer is responsible for ranking the bids starting with the ones with the lowest unit price (Energypedia 2014). GENCOs and buyers which are certified during the bidding process are guaranteed and paid a specific unit price of energy for the defined period when the certificate is valid. Additional costs incurred on such tenders are imposed on the demand side through a special levy (Sadeghi et al. 2017). One of the drawbacks of this scheme is lack of or inadequate participation. If this occurs, there is a risk of lack of competition in a tender which can consequently precipitate expensive offers and low level of implementation. As regards studies related to GEP, Pereira and Saraiva (Pereira and Saraiva 2013) have demonstrated the effectiveness of tendering mechanisms on the addition of new RES capacities across a typical planning period.

6 Emission Reduction Capabilities

An analysis of CO_2 emission avoided through the use of nuclear power generation plant since 1980 shows that 60 Gt of CO_2 has been abated. Hence, if coal- or gas-fired power plants are replaced by nuclear power generation plants, a CO_2 emission reduction of up to 2.6 gigatones can be achieved annually (NEA 2015). This represents approximately 13% of the total estimated emission reduction if a 2 °C rise in temperature is to be sustained by 2050. The CO_2 emission reduction capabilities of other technologies include CCS 19%, fuel switching and efficiency 1%, hydro 3%, solar PV 9%, CSP 7%, wind onshore 9%, wind offshore 3%, biomass 4%, electricity saving 29% and other renewables 3% (Fig. 5) (NEA 2015).

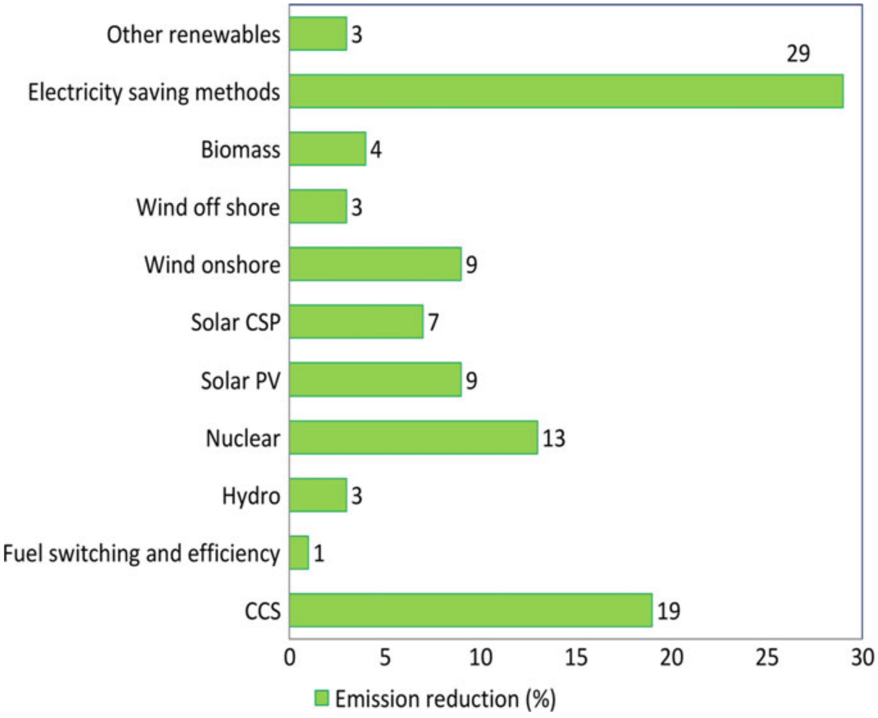

Fig. 5 Emission reduction capabilities if 2 °C rise in temperature is to be sustained by 2050

7 Decarbonisation: Both Sides of the Story

The decarbonisation of GEP comes with multiple benefits as well as drawbacks. It has the tendency to cap emissions, reduce pollution, ensure cleaner atmosphere and water and improve health, reduced energy imports, diversification and the emergence of new industry. In 2015, a total cost of €8.8 billion was saved from the importation of primary fuel due to the adoption of renewable energy (Kreuz and Müsgens 2017). Between 2013 and 2015, a 6% reduction on energy intensity was experienced in Germany and Australia as a result of the continuous adoption of energy efficiency and renewable energy (The World Bank 2018). The inclusion of renewable energy sources in the global energy mix has also encouraged the development of a huge labour market for the industry. For example, the renewable energy industry (wind, bioenergy and geothermal) in Germany was responsible for the employment of 322,000 personnel in 2016 (Ren 2015). Likewise, the renewable energy sector created 350,000 jobs in the solar related industry and another 107,000 in the wind industry in 2017 (Monyei et al. 2019). Apart from job creation, decarbonisation has significantly addressed the challenge of workforce inequity by improving enrolments into the trainee programmes of trade unions involved in the construction of

RE plants in California (Luke et al. 2017). It was also reported that a 33% increase in full-time job in renewable energy was experienced in Australia between 2015 and 2017 (Monyei et al. 2019). As reported by Monyei et al. 2019, these aforementioned benefits have come at the cost of majorly four unintentional effects. These include growing energy dependence, increasing renewable energy curtailment and capacity firming, limited GHG reductions and the increased vulnerability among some "losers".

8 Conclusion

This chapter has presented the efforts and challenges that are involved in the decarbonisation of the electric power system. A wide range of studies that chronologically present the subject of power system decarbonisation have been presented. The following are the summary of the insights drawn from this chapter:

- It is clear that there is no singular approach that can entirely be used for the decarbonisation of the grid. An integrated approach that accommodates various policies and decarbonisation technologies will enhance low-carbon electricity generation.
- The inability to set realistic targets, establish relevant regulatory frameworks and implement such frameworks will increase dependence on fossil fuels with its environmental consequences. Unrealistic targets and non-implementation of the relevant frameworks will slow down the rate of the irreversible momentum of clean energy which was highlighted by Obama in 2017 (Obama 2017).
- With the present and emerging technologies on nuclear power plant, it is the only fossil fuel source that offers the least emission. Although this can be harnessed in a carbon-constrained economy, the issues behind waste disposal, safety and likelihood of nuclear proliferation is still a barrier that must be investigated.
- Increasing the penetration of renewable energy in the global energy mix still remains an effective and vital option of power system decarbonisation. As such, more attention should be given to the development of proper policies that will target the challenges of decarbonisation as discussed by Monyei et al. (2019).
- Carbon capture and storage is crucial in the stabilisation of GHGs in the atmosphere. However, more research and governmental efforts to undertake practical demonstration of large-scale systems capable of exploring various methods for pre- and post-combustion carbon capture are necessary.

Acknowledgements The financial assistance of the National Research Foundation (NRF) through the DST-NRF-TWAS doctoral fellowship towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at are those of the authors and are not necessarily to be attributed to the NRF.

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Carbon Footprint of Brazilian Highway Network

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Abstract In Brazil, the transportation sector is based on diesel, gasoline and ethanol consumption for the road transport, which is responsible for 32.4% of total energy consumed, corresponding to 82.7 Mtep. Considering this context, this chapter aims to evaluate the carbon footprint of 52 mil kilometers of the Brazilian highway network. Real data was obtained from a recent National Traffic Counting Plan which considers a qualifying counting of vehicles, during 24 h in a 7 days period, and an origin and destination interviews performed in a total of 300 traffic survey stations. More than 17 million vehicles were counted and classified and 1,384,330 interviews were obtained. From the estimation of the annual average daily traffic for the roads under federal operation and management rules, the carbon footprint was evaluated using a bottom-up approach. The carbon footprint analysis presents more than 8500 TgCO_{2eq} emissions per day, with the major responsibility of light-duty vehicle flow which uses gasoline, ethanol and diesel as fuels.

Keywords Carbon footprint · Highway network · Road transport · CO_{2eq} emissions

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1 Introduction

With continental dimensions of 8.5 million of km^2, Brazil has a population of 190 million of people and an economy mainly based on agriculture and farming. To support more than 80% of the population living in urban areas, the development of the country was based on road transport with an extensive highway network (MCTI 2016).

According to IPCC (2014), transport emits CO_2, the most important greenhouse gas (GHG), and if global warming crosses the safety threshold of 2 °C then the consequences could be anywhere between bad and catastrophic. To keep global warming below 2 °C, atmospheric concentrations of GHGs must be stabilized and this will eventually require net zero annual emissions (IPCC 2014). Worldwide, in 2014, transport as a whole was responsible for 23% of total CO_2 emissions from fuel combustion and road transport was responsible for 20% (Santos 2017).

The GHG emissions from transportation sector has investigated by the international literature, with some studies presenting a life cycle approach (LCA) to measure energy consumption and carbon emissions and other studies analyzing the influencing factors and mitigation measures by researches and policy makers. To be highlighted in this chapter, Zhang et al. (2019) present a review of China's road traffic carbon emissions from road traffic including the top-down and the bottom-up models. They summarize the main factors that affect the traffic carbon emissions, which are divided into demand-side factors, supply-side factors and environmental measurement factors. On the other hand, Gupta (2014) estimates the carbon footprint arising from household's use of road transport in the city of Kolkata, India, across various income categories. The result shows a clear picture of per capita footprint from transport use increasing with income. Recently, Ghate and Qamar (2019) determine the life cycle environment impacts of public transport of an Indian city, occurring during the three phases (construction, operations and maintenance) of this project. The results indicate that a metro system generates more carbon dioxide emissions per passenger kilometers as compared to a bus rapid transit (BRT) system, although the metro system is more energy efficient for its full life period as compared to BRT system.

In addition, some specific studies have informed the carbon emissions from road transport, such as Solaymani (2019) which indicates that the USA and China had the highest cumulative CO_2 emissions during 2000–2015, with values of 26,998.6 and 8190.9 Mt, respectively. Also, Lv et al. (2019) analyze the driving factors of freight transport carbon emissions and the effects of urbanization on freight transport carbon emissions in China and show that the total amount of freight carbon emissions in China has increased from 3.74 Mt in 1988 to 96.42 Mt in 2016.

Nocera et al. (2018) present the TANINO model (Tool for the Analysis of Non-conservative Carbon Emissions In TraNspOrt) which consists of two different modules to optimize the results of three traffic flow single estimators and evaluate carbon emissions while taking into account road infrastructure, vehicle type and traffic conditions. TANINO is then tested to calculate CO_2 emissions along the ring road of the Spanish city of Seville, showing its more efficient performance, compared to the single estimators normally adopted for such aims.

Finally, Singh et al. (2017) present the emission inventory of GHG emissions from different vehicle categories of road transport in India, in order to identify the dominant vehicle categories responsible for emissions which would help in targeted mitigation measures. The CO_2 emissions vary from 0.17 Mt in 2001 to 0.47 Mt in 2013.

In contrast, in case of Brazil, the fossil fuel consumption by the transportation sector was responsible for 22.8% of the total CO_2 emissions in 2010, according to MCTI (2016). Figure 1 shows the participation of each sector for the total of 739.67 Mt CO_2 in 2010.

Although there are some national reports about the GHG emissions from the transportation sector, there are some difficulties in having reliable information, which could be truly representative of the real data. So, for the first time, it is possible to develop a detailed study of the carbon footprint of the Brazilian highway network under a bottom-up approach, using data from the Brazilian National Traffic Counting Plan (PNCT—*Plano Nacional de Contagem de Tráfego* in Portuguese) which is implemented by National Department of Transportation Infrastructure (DNIT—*Departamento Nacional de Infraestrutura de Transportes* also in Portuguese). The PNCT was conducted on roads under federal operation and management responsibility.

This research was structured with the objective to create a diagnosis of the road traffic from qualifying and counting surveys, which obtain statistical data from freight

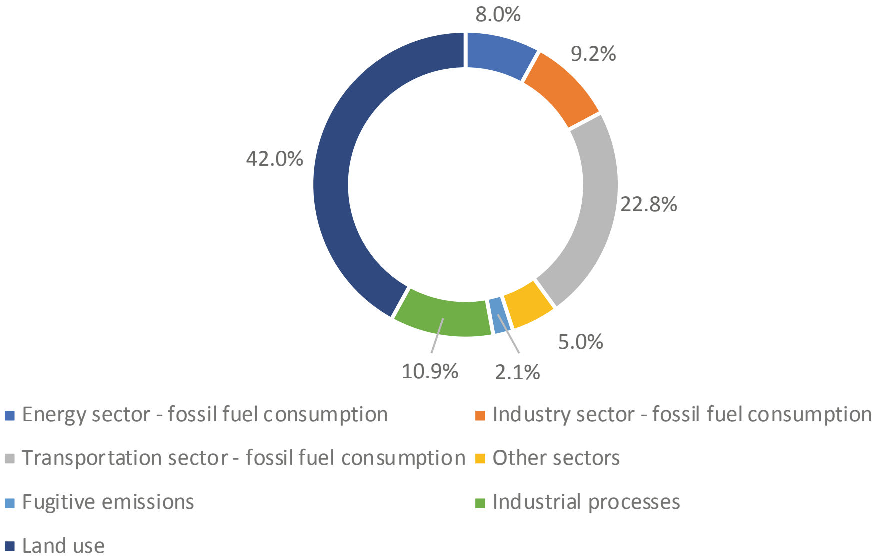

Fig. 1 Brazilian sector participation on CO_2 emissions. *Source* MCTI (2016)

and passenger transportation in highway network. Therefore, from road counting survey is possible to obtain information about the vehicle flow for each highway direction and for each time unit. Finally, information about the type of fuel used is obtained from origin and destination interviews.

The results of this study allow the quantification and characterization of carbon footprint of the entire highway network and allow the understanding of the CO_{2eq} emissions behavior, which national policies could be based on, especially, regarding the fulfillment of the Brazilian Politic about Climate Change (PNMC—Law nº 12.187/2009) and the Sectoral Plan for Transport and Urban Mobility to Climate Change Adaptation.

Therefore, after this Introduction, this chapter presents more specifically the Brazilian National Traffic Counting Plan in Sect. 2, followed by the characterization of the Brazilian road transport in Sect. 3. The carbon footprint methodology is presented in Sect. 4 and the results in Sect. 5. Finally, the main findings are presented in Sect. 6.

2 The Brazilian National Traffic Counting Plan

The National Department of Transportation Infrastructure (DNIT) is responsible for the creation and management of the PNCT, which returned its activities in 2014. Since then, 320 permanent traffic counting stations were disposed around the entire Brazilian highway network which counts and classifies vehicles 365 days, 24 h per day. Besides, DNIT has implemented 126 traffic counting stations of short period (one week only) and manual traffic surveys on 300 stations where a sample of the origin and destination of the vehicles was obtained.

Then, the main assignments of PNCT are:

- Vehicle flow evaluation to establish traffic tendencies, seasonality and future behavior;
- Policy transportation definitions;
- Road transport capacity analysis and service level study;
- Pavement design, cross-section and safety devices; and
- Location study for weighing stations.

A research group of Federal University of Rio de Janeiro (COPPE/UFRJ) works as a partner of DNIT to create the methodology of vehicle flow estimation, based on georeferenced database, besides statistical data treatment. In addition, this group is responsible for planning activities to support in terms of road operation and safety.

It is important to highlight that the classification of vehicle is based on traffic national resolutions (CONTRAN nº 210, 211 and 259; DENATRAN 086/2006), then the categories which are considered on this present study are:

A. Commercial bus and truck with two drive shafts: simple bus and simple truck;

B. Commercial bus and truck with three drive shafts: bus, simple truck and truck plus semitrailer;
C. Freight vehicle combination with four drive shafts: simple truck, truck plus semitrailer, truck plus trailer and truck plus two semitrailers;
D. Freight vehicle combination with five drive shafts: truck plus semitrailer, truck plus trailer, truck plus semitrailer and trailer and truck plus two semitrailers;
E. Freight vehicle combination with six drive shafts: truck plus semitrailer, truck plus trailer, truck plus semitrailer and trailer and truck plus two semitrailers;
F. Freight vehicle combination with seven drive shafts: truck plus trailer, truck plus two semitrailer, truck plus semitrailer and trailer and truck plus two trailers;
G. Freight vehicle combination with eight drive shafts: truck plus two semitrailers, truck plus semitrailer and trailer and truck plus two trailers;
H. Freight vehicle combination with nine drive shafts: truck plus two semitrailer, truck plus semitrailer and trailer and truck plus three trailers;
I. Light and commercial vehicles; and
J. Motorcycles.

Next section presents more information about the permanent traffic counting stations and about the origin and destination surveys performed by DNIT.

2.1 Permanent Traffic Counting

PNCT is responsible for installing in the Brazilian highway network 320 traffic data collection stations with sensors operating continuously. A computational system was designed by the research group of COPPE/UFRJ in order to data collection, transfer and validation of the information. From that, it is possible to estimate the annual average daily traffic (AADT) for the entire highway pavemented network under public management, which has more than 5 thousand segments. For more details, see Ramos et al. (2018).

The data collection is performed by permanent traffic counting stations placed in specific points of the road network, which receive piezoelectric sensors. These stations are responsible to get information about the quantity for each category, velocities and weights (total gross weight and the weight by drive shafts). In addition, the traffic counting of short period was performed in 126 stations, based on pneumatic sensors, in order to cover a specific region in such a way to complement the information of permanent traffic counting.

Using the information from the traffic counting stations, the flows were estimated for all federal highways by a mathematical process which considers the origin and destination trip table (seed trip table), the road network with costs in the arcs and local road segments with known traffic flow. This process was performed using software TransCAD.

However, some of the data collected by the stations presented abnormal behavior, such as missing data. To correct these failures, an imputation data multi-category methodology was developed which follows the Gaussian method for temporal series (Ramos et al. 2018). This process allows to catch temporal correlation in the same time that deals with non-stationary and seasonal nature of traffic, with 95% confidence degree.

So, as the inherent structure of a traffic count time series can change along some time, different models for imputation are chosen to work on 45-days consecutive time windows. The model selection step performs a tournament between models based on the comparison of the imputation of synthetic gaps and the real data applying a Percentage Absolute Error (PAE).

Figure 2 presents the multi-category imputation methodology used, which is motivated by the following factors, and Fig. 3 shows an example of data treatment:

- The use of Passenger Car Equivalent representation for traffic count data to introduce a smoother scenario on the resulting time series;
- Pre-processing step to get outliers and avoid bad training data for Gaussian Process (GP) regression; and
- Stack of GP-models to be selected by competition as one does not have previously preferences.

2.2 Origin and Destination Survey

The origin and destination survey is based on 300 stations which were spread all over the Brazilian highway network. The interviews were made by representants of the Brazilian army using electronic devices, and it was developed in four phases:

- Phase 1: July 2–8, 2016, in 59 stations;
- Phase 2: November 19–25, 2016, in 58 stations;
- Phase 3: July 1–7, 2017, in 117 stations;
- Phase 4: November 18–24, 2017, in 66 stations.

Firstly, the origin and destination survey has a vehicle identification and a characterization interview approach, followed by travel characterization and motivation, income of the driver and specific characterization of the transport operation.

From the interviews, it is possible to characterize the traffic in terms of the identification of the origin and destination of the trips, the socioeconomic profile of the driver, the load characteristics of the freight transport and the behavior of the passenger. As for each station a vehicle counting is performed, this data can be used to complement the information of the traffic flow in some network segments.

Figure 4 presents all the 300 stations which result in more than 17 million of vehicles counted and classified and more than 1.3 million of interviews. The following section summarizes the main results obtained and characterizes the Brazilian road transport.

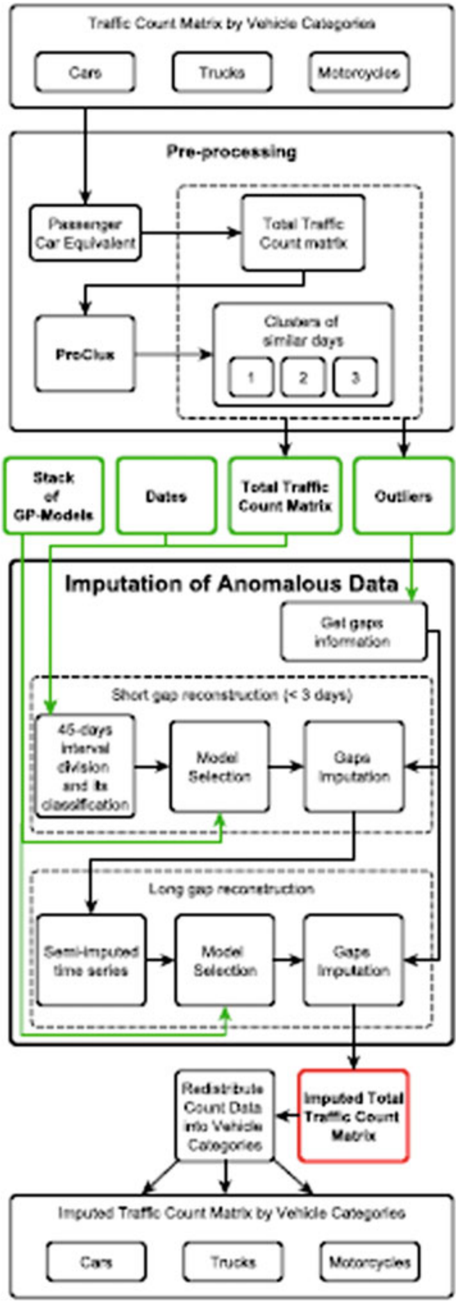

Fig. 2 Multi-category imputation scheme with Gaussian Process models. *Source* Ramos et al. (2018)

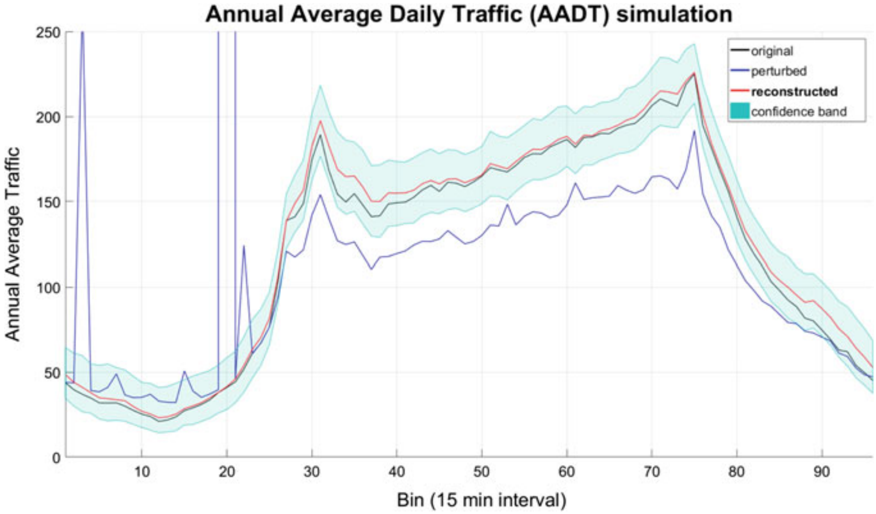

Fig. 3 Example of traffic flow after imputation phase. *Source* Ramos et al. (2018)

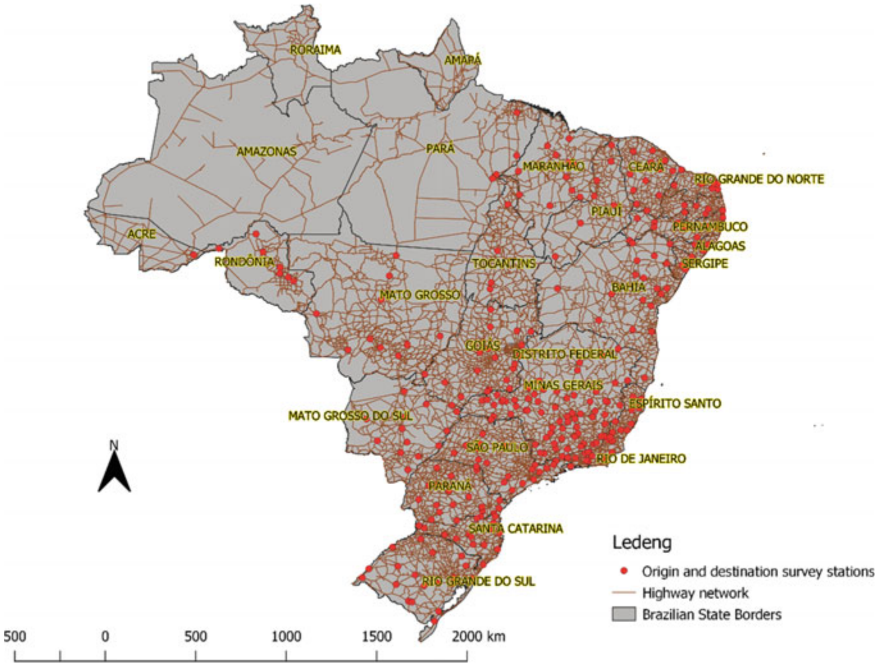

Fig. 4 Origin and destination survey stations

3 Brazilian Road Transport

The Brazilian transportation sector is characterized by intensive participation of the road transport, with around 50 million of light commercial vehicles and 2 million of freight vehicles in 2012 (BRASIL 2014). The evolution of the fleet around the years can be seen in Figs. 5 and 6, according to the national inventory of atmospheric pollutants of road transport.

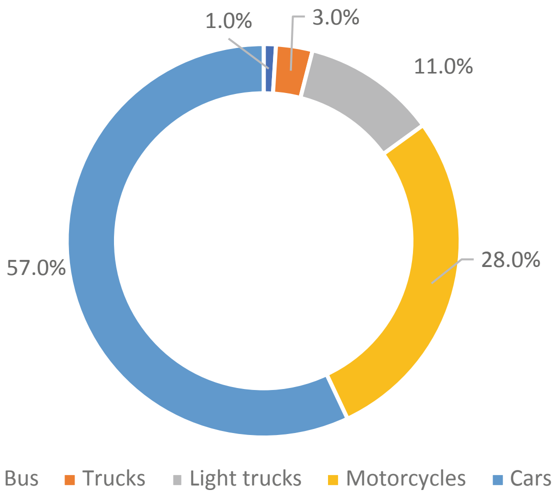

Fig. 5 Light vehicle fleet, in 2012. *Source* BRASIL (2014)

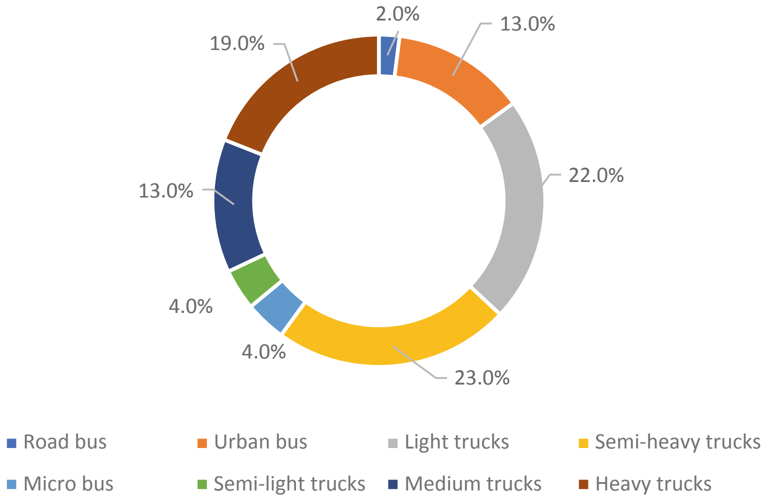

Fig. 6 Freight vehicle fleet, in 2012. *Source* BRASIL (2014)

As mentioned before, the traffic flow behavior of the Brazilian highway network was estimated for passenger and freight vehicles together. Using data of the origin and destination survey, Table 1 and Fig. 7 show the total of vehicle counted per each phase of the project and per each considered category.

Moreover, at the end of 2017, the total of vehicles interviewed, by the origin and destination survey, was 5,884,652 for Category A; 5,791,202 for Category B; 2,448,953 for Category C; 2,793,656 for Category D; 4,191,860 for Category E; 1,791,918 for Category F; 60,405 for Category G; 949,133 for Category H;

Table 1 Total of vehicles in each phase of the origin and destination survey

Category	Phase			
	1	2	3	4
A	1,088,522	704,586	2,677,933	1,413,611
B	964,412	749,540	2,458,027	1,619,223
C	455,578	296,968	1,031,977	664,430
D	367,848	321,997	1,218,641	885,170
E	909,414	608,435	1,476,686	1,197,325
F	489,756	214,122	621,686	456,354
G	15,562	12,662	21,042	11,139
H	211,014	207,692	312,340	218,087
I	9,467,452	4,963,561	16,833,037	9,535,059
J	479,719	489,666	1,326,085	715,083

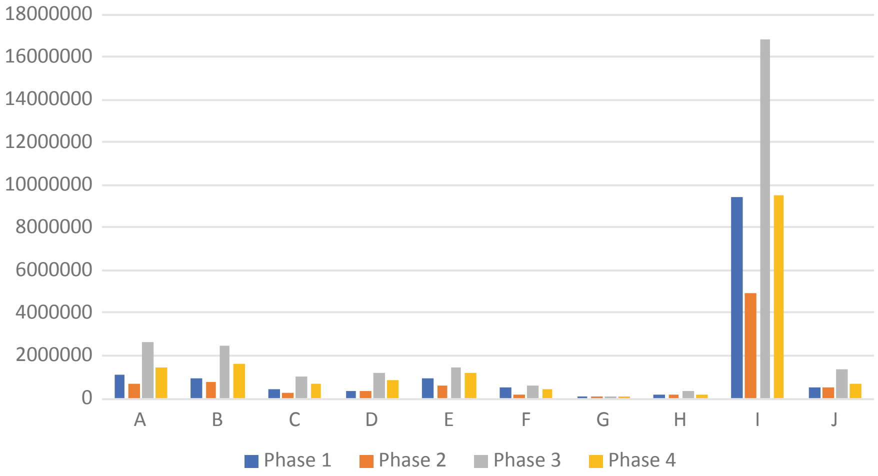

Fig. 7 Total of vehicles in each phase of the origin and destination survey

40,799,109 for Category I; and 3,010,553 for Category J. Therefore, Fig. 8 shows the total of vehicle counted in each phase. It possible to note that, because of the large number of stations placed, Phase 3 is responsible for around 40% of the total of vehicles.

After applying the mathematical process presented in Sect. 2, the total flow for each federal road segment is shown in Fig. 9. It is possible to observe that the largest flows reported are presented in south and southeast regions of the country.

Using the origin and destination data of the PNCT, it is possible to observe also the use of each type of fuel, per each category of vehicle in each station, located in the Brazilian network. From that, we can conclude that all categories related to freight vehicles (Categories A to H) uses diesel, with an expressive participation of Categories A and B. However, all the stations, independently of phase, show the intensive use of gasoline and diesel (around 50% of the total of drives interviewed) by light vehicles (Category I) and some participation of ethanol use.

Because of the significant flow reported, PNCT also allows to evaluate the passenger trip reasons, which is presented in Fig. 10. We can note that the majority of the travels is made with work proposes, followed by recreation.

4 Carbon Footprint Methodology

Carbon footprint is defined as “a methodology to estimate the total emission of greenhouse gases in carbon equivalents from a product across its life cycle from the production of raw material used in its manufacture, to disposal of the finished product (excluding in-use emissions)” (Carbon Trust 2006).

According to IPCC—Good Practice Guidance (IPCC 2007), there are two types of methodology to estimate the GHG emissions from transportation activity: from the energy consumption of each type of fossil fuel which is consumed per vehicle (“top-down” approach) and from the total of flow estimated and the traveled distance per each type of vehicle (“bottom-up” approach). The bottom-up model is theoretically more accurate and reflects the characteristics of mobile source emissions (Zhang et al. 2019).

PNCT has information about the traffic flows on each segment of the Brazilian road network; consequently, the bottom-up methodology was selected for this work to estimate the carbon footprint. The LCA framework was used for analyzing GHG emissions of the Brazilian highway network considering the CO_2, CH_4 and N_2O. For this analysis, only the operation of highways (rolling stock movement of the vehicles) is considered on the scope and the GHG emissions are estimated based on annual average of vehicle flow, which is based on data of 2017.

So, firstly, Eqs. 1 and 2 present the quantification of CO_2 and of CH_4 and N_2O emissions used, respectively, per each vehicle type (represented by “*i*”) and each type of energy source (represented by “*j*”).

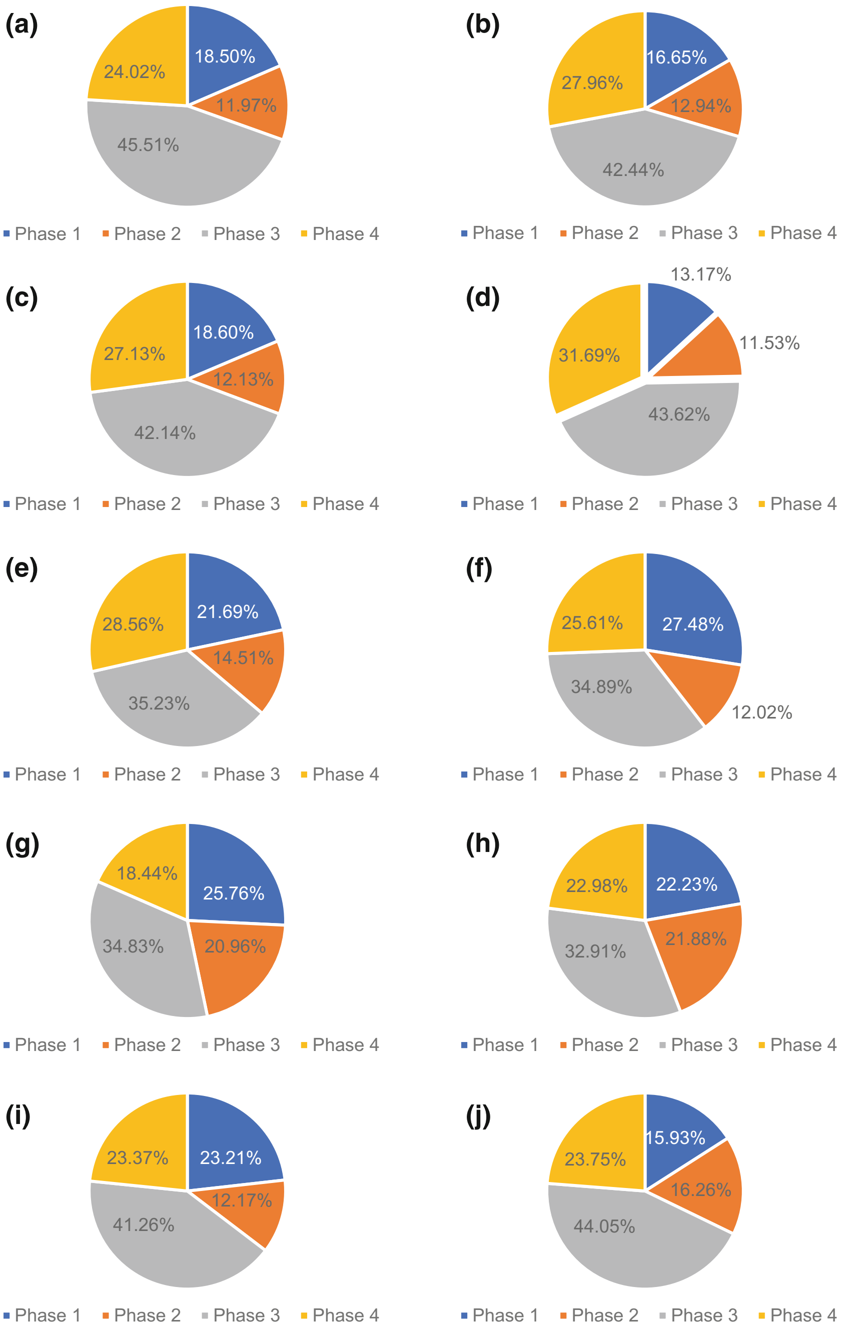

Fig. 8 Participation of the total of vehicle counted by phase, for each category

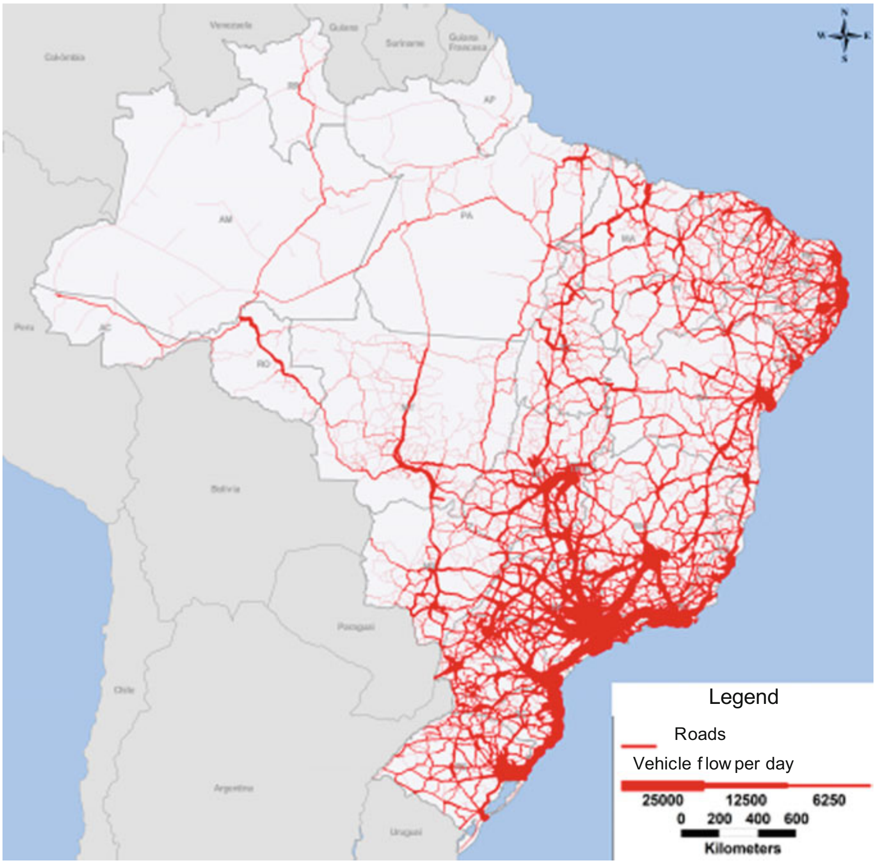

Fig. 9 Total of traffic flow measured in 2017, in federal highways

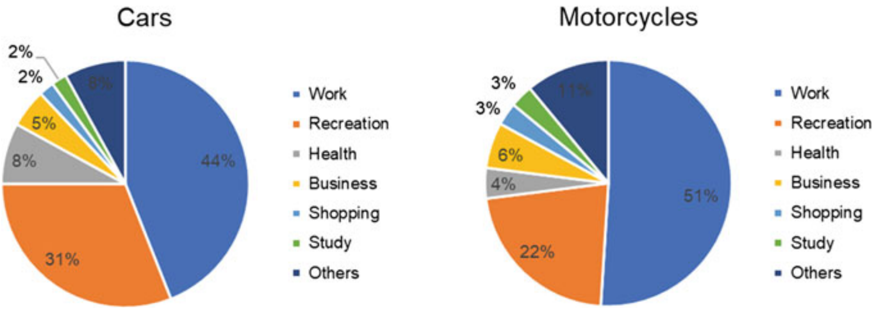

Fig. 10 Travel proposes for cars and motorcycles in federal highways

$$E_{CO_2,ij} = d_i \times f_i \times c_{ij} \times FE_{ij} \tag{1}$$

where

i	Vehicle types such as light-duty vehicles (cars, motorcycles and dual-fuel vehicles—categories I and J) and heavy-duty vehicles (buses and trucks—categories A to H);
j	Energy source such as ethanol, gasoline and diesel for categories I and J and diesel for categories A to H;
E_{CO_2} (kg/day)	CO_2 emissions;
d (km/vehicle)	Traveled distance for each category of vehicle;
f (vehicle/day)	Annual average daily traffic for 2017 which is computed for the Brazilian highway network, for each category of vehicle;
c (l/km)	Fuel consumption for each category of vehicle and each type of fuel consumed; and
FE (kg/l)	CO_2 emission conversion rate

$$E_{CH_4,N_2O,\,ij} = d_i \times f_i \times FE_{ij} \tag{2}$$

where

E_{CH_4,N_2O} (g/day)	CH_4 and N_2O emissions;
d (km/vehicle)	Traveled distance for each category of vehicle;
f (vehicle/day)	Annual average daily traffic for 2017 which is computed for the Brazilian highway network, for each category of vehicle; and
FE (g/km)	CH_4 and N_2O emission conversion rate

The carbon footprint counted the CO_{2eq} emissions from the sum of CO_2 emissions with the CH_4 and N_2O emissions, which considers the conversion from the global warming potential (GWP) of CH_4 and N_2O greenhouse gases, in relation to the CO_2 basis (IPCC 2010). So, Eq. 3 shows the carbon footprint calculation.

$$C_{\text{footprint}} = \sum E_{CO_2} + \left(21 \times \sum E_{CH_4} + 298 \times \sum E_{N_2O}\right) \times 10^{-3} \tag{3}$$

where

$C_{\text{footprint}}$ (kg_{COeq}/day)	Carbon footprint of the Brazilian highway network;
E_{CO_2} (kg/day)	CO_2 total emissions;
E_{CH_4} (g/day)	CH_4 total emissions; and
E_{N_2O} (g/day)	N_2O total emissions

For these calculations, the traffic flows are based on permanent traffic counting stations, and the traveled distances are based on the origin and destination surveys, both of the PNCT. The fuel consumption depends on the category and type of fuel used by each vehicle which is obtained using data of the origin and destination surveys. The FE emission conversion rates considered in this work are based on

Table 2 Fuel consumption per each type of vehicle category and fuel

Category	Fuel type	Fuel consumption (l/km)	FE_{CO_2} (kg/l)[c]	FE_{CH_4} (g/km)[c]	FE_{N_2O} (g/km)[c]
A, B, C, D, E, F, G, H	Diesel	0.3268[a]	2.631	–	–
I	Diesel	0.0951[b]	2.631	–	–
	Gasoline	0.0895[c]	2.234	0.0373	0.0211
	Ethanol	0.1225[c]	1.512	0.1630	0.0095
	Dual-fuel	0.0803[c]	2.234	0.0121	0.0196
J	Gasoline	0.0270[c]	2.234	0.0719	0.0020
	Dual-fuel	0.0242[c]	2.234	0.0330	0.0020

Source [a]Cunha et al. (2017), [b]INMETRO (2018), [c]BRASIL (2014)
Obs: It is considered here that dual-fuel vehicles which are counted by PNCT use mainly gasoline fuel

BRASIL (2014). Thus, Table 2 summarizes the fuel consumption and FE emission conversion rates considered in this work.

5 Results and Discussion

Firstly, we present the average daily vehicle flow per each type of vehicle category use, in Fig. 11. It is reported from PNCT that heavy-duty vehicles, which is represented by categories A, B, C, D, E, F, G and H, uses only diesel fuel. On the other hand, light-duty vehicles are represented by categories I (cars) and J (motorcycles), which could use gasoline, ethanol or diesel. Both categories I and J could also be dual-fuel. So, Fig. 12 presents the intensity of fuel use based on the behavior of the vehicle flow.

From Figs. 11 and 12, because of more than half of total flow is represented by cars (category I), it is possible to conclude that gasoline has the major intensity of use, followed by dual-fuel vehicles. In addition, the use of gasoline is almost three times and six times more than the use of diesel and ethanol, respectively. On the other hand, light-duty vehicles are responsible to consume 80.8% of diesel fuel, in contrast with all eight categories of heavy-duty vehicles which correspond to 35.3% of the average daily flow and consume 19.2% of diesel.

Considering this intensity of use, Fig. 13 shows CO_2 emissions from heavy-duty vehicles and Figs. 14 and 15 present the CO_2 emissions for light-duty vehicles, using diesel or other fuels. These emissions consider the average daily flow total of 2017 as mentioned before.

We can conclude that the majority of CO_2 emissions is from light-duty vehicles with gasoline, ethanol and dual-fuel (73.14%), followed by the light-duty vehicles with diesel (14.71%) and heavy-duty vehicles (12.15%). If we consider the sum of all light-duty vehicle emissions, they are responsible for 87.85% of the total of CO_2 emissions.

It is important to highlight the difference between Fig. 14 and Figs. 13 and 15 in terms of CO_2 emission distribution in Brazilian regions. While Fig. 14 shows intensive CO_2 emissions from Brazilian megacities surroundings in comparison with more distant regions, Figs. 13 and 15 present considerable CO_2 emissions from these distant regions. We could infer that these emissions are related to freight transport, which uses much more the highway network in comparison with passenger transport.

We present now the CH_4 and N_2O emissions calculated for vehicles which use ethanol, gasoline and for those that are dual-fuel. So, these are light-duty vehicles and which are responsible for the emissions presented in Figs. 16 and 17.

Analyzing Figs. 16 and 17, we can see that light-duty vehicles are responsible for the emissions of 0.32 Mt CH_4/day and 0.018 Mt N_2O/day, which corresponds to a total of 13.62 Mt CO_{2eq}/day. For both CH_4 and N_2O emissions, the origin of these emissions is from Brazilian megacities surroundings.

Therefore, considering the conversion to CO_{2eq} to sum with the CO_2 emissions, the resulted carbon footprint of the entire Brazilian highway network is presented in Fig. 18.

Thus, the carbon footprint of the Brazilian highway network presents a total of 518.45 Mt CO_{2eq}/day. Heavy-duty vehicles, which use mostly diesel daily, are responsible for only 0.73%, but the majority of the emission are coming from light-duty vehicles with gasoline and ethanol fuels.

It is possible to compare these results with the CO_2 emissions indicated in literature, for China. Solaymani (2019) indicates the total of 8190.9 Mt during the period of 2000 and 2015 for transport sector, which is close to the total of CO_{2eq} emissions from a day in Brazilian highways, if we consider a average of 546.06 Mt CO_2/year.

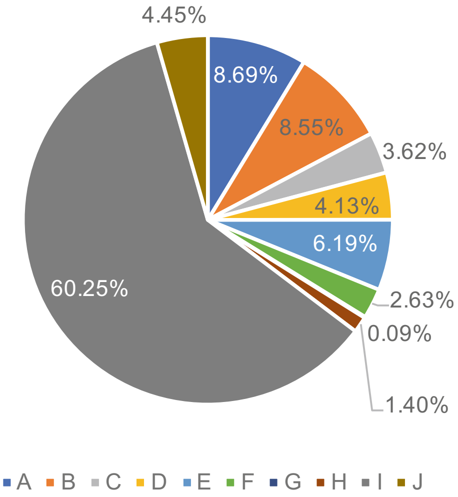

Fig. 11 Average daily flow, per vehicle category

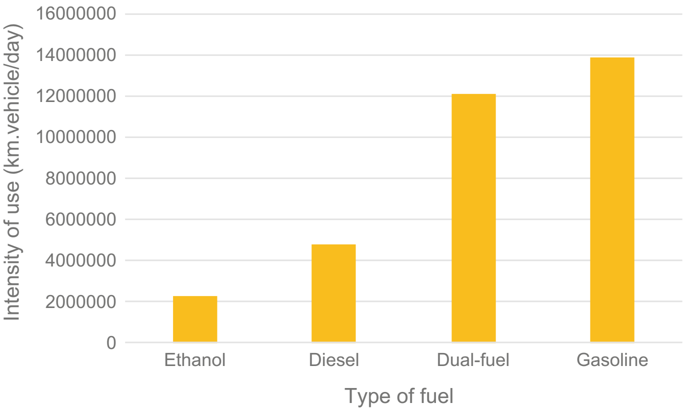

Fig. 12 Intensity of fuel use

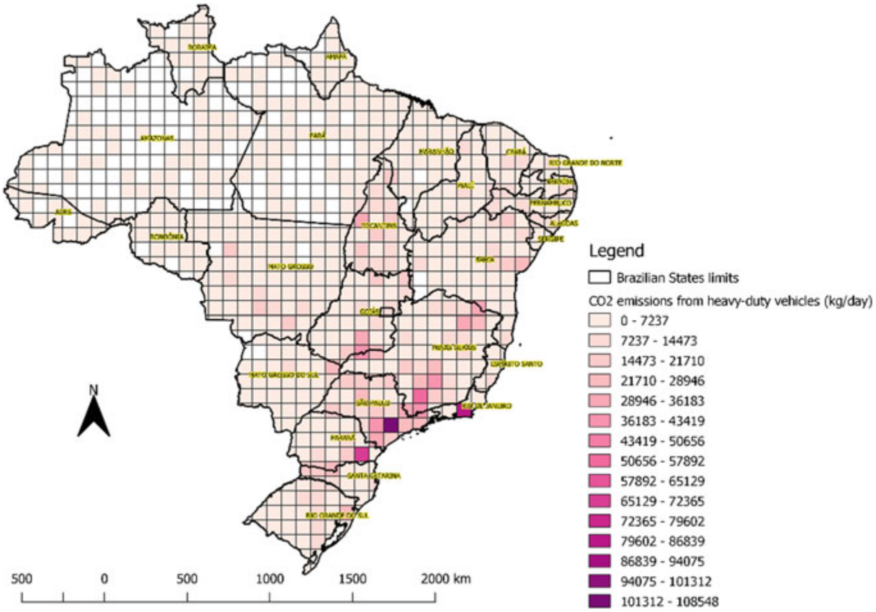

Fig. 13 CO_2 emissions from heavy-duty vehicles, considering diesel use

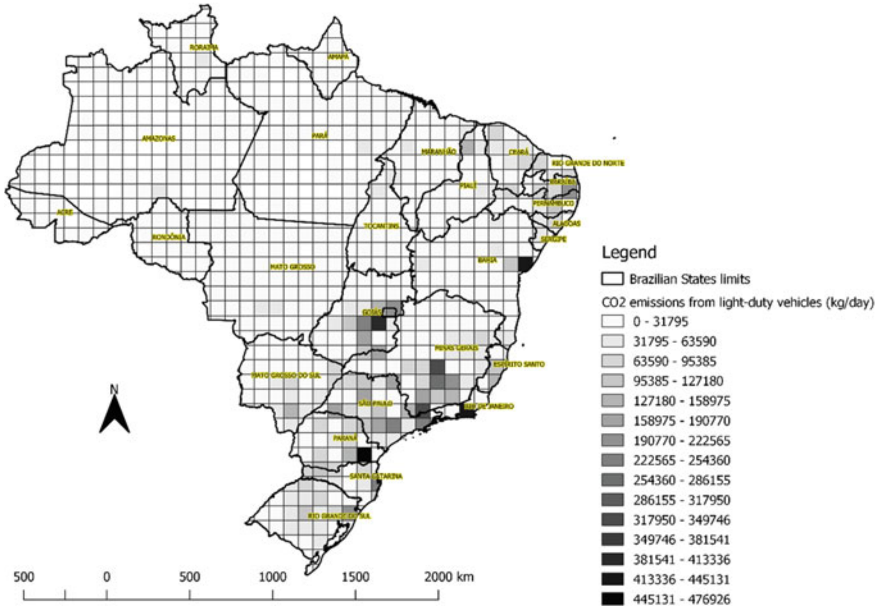

Fig. 14 CO_2 emissions from light-duty vehicles, considering uses of ethanol, gasoline and dual-fuel

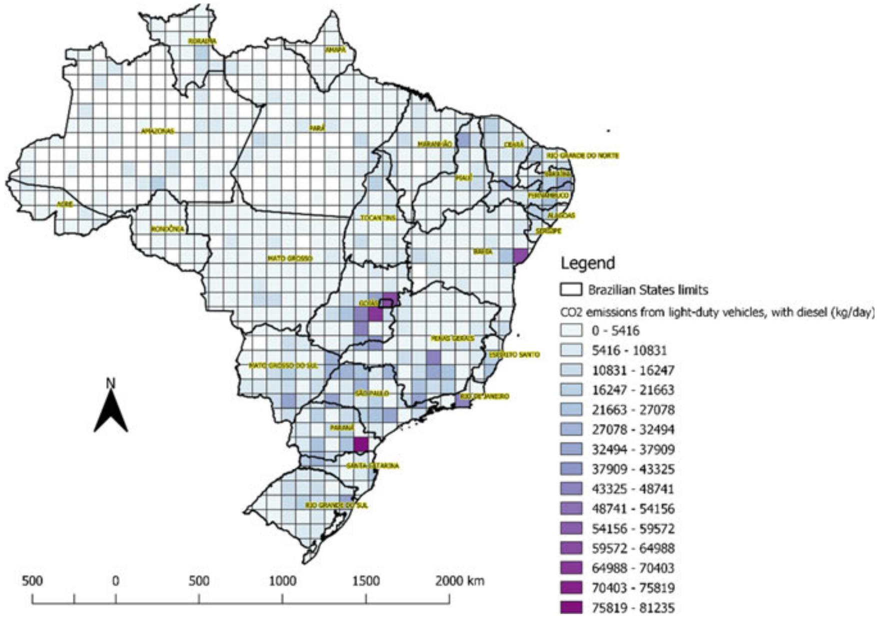

Fig. 15 CO_2 emissions from light-duty vehicles, considering diesel use

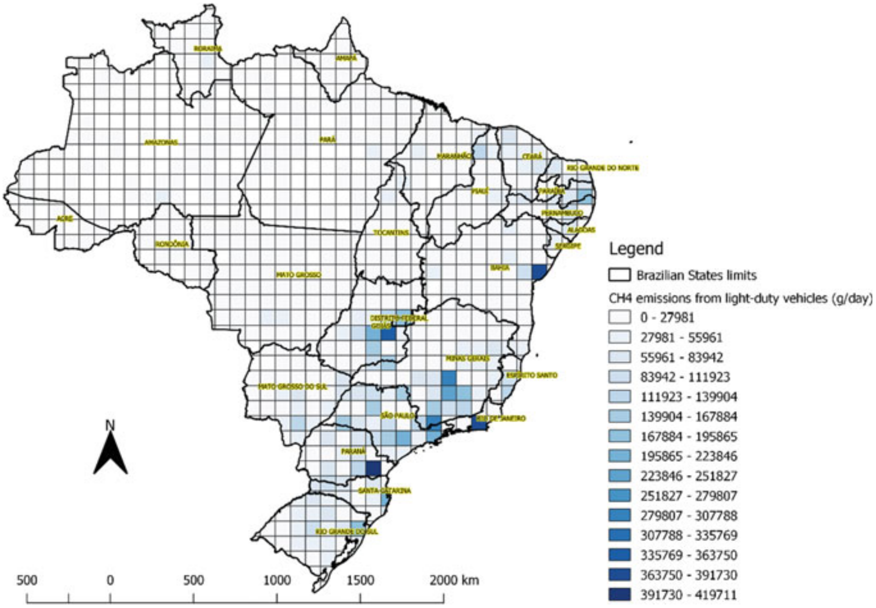

Fig. 16 CH_4 emissions from light-duty vehicles

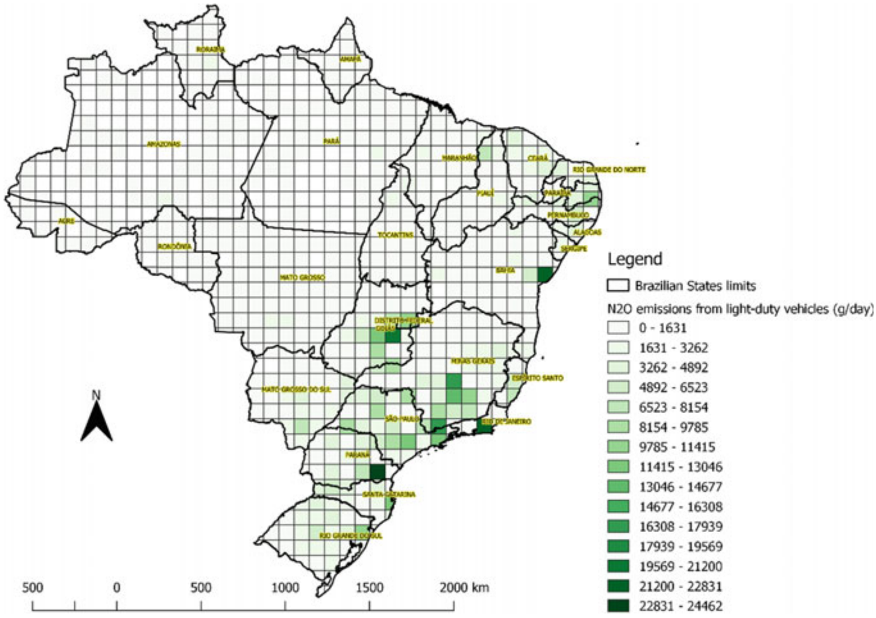

Fig. 17 N_2O emissions from light-duty vehicles

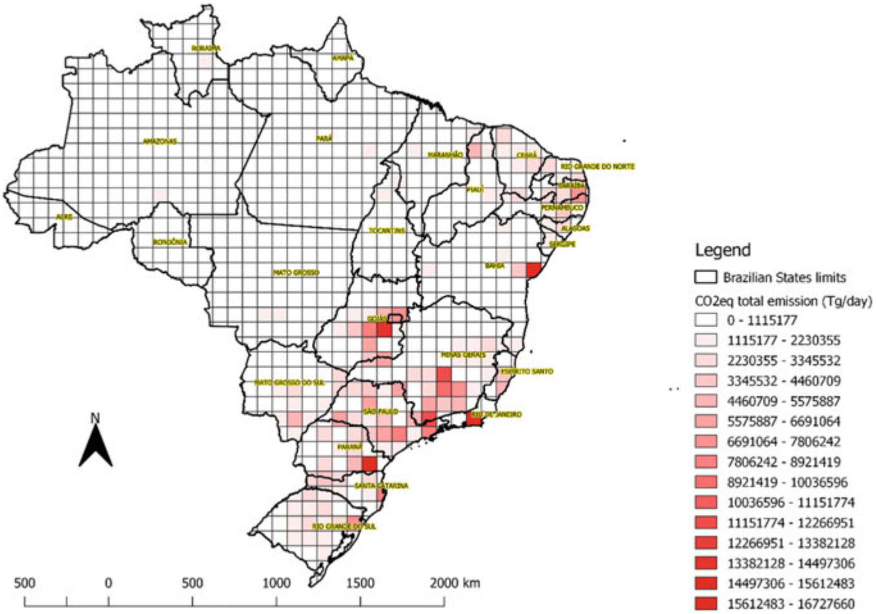

Fig. 18 Carbon footprint of the Brazilian highway network

Also, Lv et al. (2019) observe the freight carbon emissions in China varying from 3.74 Mt in 1988 to 96.42 Mt in 2016. Therefore, the total emissions, in one day, from Brazilian highways is more than five times of carbon emissions from Chinese freight transport in a year of operation.

Also, it is important to observe that the carbon footprint also follows the vehicle flow tendency, with high contributions of south and southeast Brazilian regions. On the other hand, Fig. 18 highlights intensive CO_{2eq} emissions around Brazilian megacities, such as Rio de Janeiro, São Paulo, Brasília, Curitiba and Salvador, coming from relevant federal highways, which connects south and southeast regions with northeast and midwest regions, providing a significant contribution to the carbon footprint. We can see these results given a high participation of light-duty vehicles in the total average daily flow.

6 Conclusions

The data of the Brazilian National Traffic Counting Plan which covers the national network, mainly the federal highways, was used to compute the carbon footprint resulted from the fossil fuel consumptions by the vehicles.

From the analysis of the results, it is possible to conclude that the major responsible for the CO_{2eq} emissions is the light-duty vehicle flow, showing around 90% of the total of 518.45 Mt CO_{2eq}/day emitted. Also, road freight transport, which Brazilian logistics and supply chain are mainly dependent, has a considerable amount of 62.97 Mt/day of CO_{2eq} emissions.

Having in mind these highlights, it is essential to develop commercial and public policies in order to decarbonize the Brazilian road transport sector, especially with focus on passenger transport. According to Santos (2017), carbon pricing is an essential but not sufficient condition to achieve a substantial reduction in GHG emissions. Subsidies both to clean technologies and to Research and Development of clean technologies, and regulations are also essential as the time window is rapidly closing (Santos 2017).

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