Journal of Cleaner Production 374 (2022) 133409

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Introducing the total efficiency to address challenges of the 21st century

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ARTICLE INFO

Handling Editor: Prof. Jiri Jaromir Klemeš

Keywords:
Efficiency
Total efficiency
Power plants
Fossil fuels
Renewable energy sources
Life cycle assessment

ABSTRACT

The evaluation and comparative analyses of energy conversion technologies are carried out with well-established concepts, like the concept of efficiency. Today, however, new technologies based on renewable energy sources challenge conventional approaches. Accounting for fuel diversity and other inequalities can ensure that comparative analyses result in trustworthy results. This paper aims to address this issue by updating conventional efficiency for more accurate comparative evaluations of fossil fuel energy systems. Specifically, the concept of total efficiency is introduced to account for extraction, processing and transportation of fossil fuels, aspects that are not currently considered in the conventional definition of efficiency. The total efficiency is determined by studying the environmental impacts of these processes and quantifying their energy requirements in terms of additional fossil fuel use. Two case studies in Spain are presented to demonstrate the impact of using the developed method on efficiency estimates. The total efficiency is found to be lower than the convectional efficiency by 21–25% to up to 41%, in the most unfavorable cases. This shows the significant impact of the preparation steps of fossil fuels and represents a fairer comparison between fossil fuels and renewable conversion processes.

1. Introduction

Thermodynamic analysis is used to evaluate energy systems, by identifying the principal sources of inefficiencies and losses. First- and second-law efficiencies are strong tools of thermodynamic analyses and can be applied to different types of systems (Petrakopoulou and Tsatsaronis, 2012; Petrakopoulou et al., 2016). As such, numerous policies define sustainability, energy security, and competitiveness goals using efficiency (IEA, 2018; European Commission, 2012; Godínez-Zamora et al., 2020; Sodiq et al., 2019; Poggi et al., 2017). Efficiency is also useful as an indicator of economic and environmental performance, since higher values of efficiency are associated with the more effective use of resources, i.e., lower costs and emissions, higher production, and more effective land use. However, while efficiency has been a universally useful concept in comparative studies of fossil fuel and nuclear plants, its theoretical bases and use as a sustainability measure is challenged today by a transitioning energy sector and renewable energy (Godínez-Zamora et al., 2020; Malinauskaite et al., 2019; Lackner et al., 2021; Patterson, 1996).

Renewable energy sources (RES) and fossil fuels have strongly distinct characteristics. RES have zero fuel cost, are locally available but intermittent and close-to-zero direct emissions. Fossil fuels, on the other hand, are always available, but they need to be acquired and appropriately processed before use. Fossil fuel preparation steps consist primarily of the extraction, the processing, and the transport of fuel, with processing representing a small fraction of the total energy expenditure (Apostolos et al., 2013). The weight of preparation steps is also apparent in industries other than the energy sector, where efforts are made to minimize their overall impact (Dörr et al., 2013; Li et al., 2016; Shin et al., 2017). Fuel preparation steps may be included in performance indicators similar to efficiency in studies of the lifecycle environmental behavior and economic metrics of energy systems. In the same way that the energy input necessary to produce hydrogen or biofuels should be accounted for in comparative analyses, the fuel input to make fossil fuels ready for use needs to be considered as well. An important factor that makes this realization even more important today is that the strong shift towards natural gas (NG) use, in place of coal, is associated with longer transport distances and preparation needs (e.g., liquefaction) inherently linked to considerable amounts of input energy. Road transportation and truck, in particular, can be associated with almost a third of the total exhaust emissions from transportation (Palander et al., 2020).

To comprehend the information included in the calculation of the efficiency, its basic definition needs to be examined. Efficiency (instant efficiency) is the ratio of the useful product generated at one moment to the fuel used to generate it: $efficiency = \frac{Useful\ product}{Input\ fuel}$. First and second-law

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https://doi.org/10.1016/j.jclepro.2022.133409
Received 9 February 2022; Received in revised form 16 July 2022; Accepted 30 July 2022

Nomenclature

CCPP	Combined Cycle Power Plant
DWT	Deadweight Tons
EROI	Energy Return On Investment
FFPP	Fossil Fuel Power Plant
HFO	Heavy Fuel Oil
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
NG	Natural Gas
MGO	Maritime Fuel Oil
MMscfd	Million Standard Cubic Feet per Day
PV	Photovoltaic
RES	Renewable Energy Sources

efficiency is here referred to as conventional efficiency. Whether we talk about energy or exergy efficiency, it is common practice to exclusively refer to the product and fuel of the energy conversion process within the strict limits of the power plant, ignoring any preceding or following processes (Dimopoulos et al., 2012; Dubey et al., 2021; Abo-Elfadl et al., 2020; Whiting et al., 2017). Conventional efficiencies of fossil-fuel power plants (FFPPs) are commonly higher than those of plants using RES. For example, reported efficiencies of solar plants are in the range of 10–20%, when photovoltaic systems are included (Meral and Diner, 2011; Zhou et al., 2014; Padmavathi and Daniel, 2013), or around 30% when solar thermal systems are considered. Wind turbines are reported with average efficiencies of 20–40% (EPA, 2013) and could never surpass 59% (Wagner, 2018). Combined-cycle power plants (CCPP), on the other hand, are reported to reach efficiencies higher than 60% (Millas, 2017; Kwon et al., 2020). Conventional efficiencies, however, fail to account for the different characteristics of the energy sources and can lead to inconsistencies. This creates the need for tools with a lifecycle perspective that can address the new challenges of the energy sector.

The lifecycle perspective is very common in environmental analyses. For example, life cycle assessment (LCA), accounts for the overall lifetime and different processes that affect the input fuel and generated product. There exist different approaches to an LCA based on user-defined limits: well-to-tank analyses that study the environmental impact of fossil fuels up to the stage before their use in power plants, tank-to-wheel analyses that include the operation of power plants, and cradle-to-grave analyses that include the previous two, as well as disposal or recycling. However, LCA methods do not provide straightforward performance indicators of energy systems. In the energy field specifically, the energy return on investment (EROI), first introduced by Dr. Charles A.S. Hall in 1981 (Murphy, 1098; Mitsch et al., 1981), includes energy inputs for construction, operation, and end-of-life management. However, it does not account for the energy contained in the fuel nor the acquisition and transport of fuel. The recently proposed lifetime efficiency of a plant accounts for the total energy consumed for the construction, operation, and end-of-life management of a plant (Husein et al., 2020). Although the construction of a plant has some environmental impact, it has been shown that this impact is negligible compared to the impact of the operation of fossil fuel plants (Petrakopoulou et al., 2012a, 2012b; Torres and Petrakopoulou, 2022). A shortcoming of the lifetime efficiency is that it does not account for the acquisition and transport of the fuel used in the plant. In addition, it uses the CO_2 efficiency of the plant as the indicator for the fuel used for its construction, operation, and end-of-life management, making the approximation that all of these phases are covered by an identical plant with the same structure, fuel, and efficiency. This, however, can lead to inaccuracies, since the fuels and the energy conversion processes put into use in these phases may vary significantly. CO_2 emissions can be used as an approximation when the input fuel mix is known, remains constant and can allow comparisons under similar bases. For the US fuel mix, for example, NETL reports that around 20% and 6% of the total equivalent CO_2 emissions for natural gas and coal plants, respectively, are due to acquisition and transport of fuel ($Fuel_{ac+trans}$). For plants with CO_2 capture, on the other hand, this percentage may vary significantly and reach 60% (Skone et al., 2011). It is obvious then that assuming that the lifecycle of each of these plants is supported by an identical plant, will have a strongly negative impact on the plant with CO_2 capture and will, most probably, not lead to accurate results.

The total efficiency defined in this work, adopts the preparation steps of fossil fuels, recognizing the characteristics of individual power plants and regions. The goal is to adapt conventional efficiency into a concept that accounts for evolving challenges in the energy sector and accounts for different technological and operational characteristics of the fuels and facilities of the 21st century. Metrics with such characteristics are researched to help the shift of the energy world to more sustainable solutions based on renewable sources (Ritchie et al., 2020), and measures that will help decelerate climate change (Linares and Labandeira, 2010). It is expected that total efficiency will constitute a step towards fairer evaluations of energy systems, in general, and, more specifically, more just comparisons between RES and fossil fuels.

2. Methods

The approach introduced in this work demonstrates how to calculate the total efficiency. The evaluation of the preparation steps of fossil fuels relies on the estimation of the additional fuel input required to realize these steps and their associated environmental impact based on LCA studies. This work is based on well-to-tank LCA studies.

Involved processes are split here into direct and indirect processes based on the additional energy input they require. Direct processes refer to processes that need additional input of fossil fuels, e.g., freight and passenger transportation that are strongly dependent on oil derivatives worldwide. Indirect processes, on the other hand, refer to processes where electricity to drive machines is needed. In the latter case, the fuel mix used to generate the electricity must be accounted for (Cust et al., 2017; Ritchie et al., 2020). Data on these processes are collected from published environmental analyses on the topic (see Appendix B).

The total energy consumption for the preparation of a fossil fuel is calculated with Equation (1), summing up all equivalent energy of the fossil fuels used directly and indirectly during the steps of extraction, processing, and transportation. The direct energy consumption is based on the fossil fuel used per unit of mass of processed fuel of each stage (e.g., metric tons of diesel used to extract one metric ton of coal). The total direct fuel used is then the sum of the energy content of each fuel (first part of the right side of Equation (1)). The total energy content of each fuel is estimated by multiplying the amount of fuel with its lower heating value. The indirect consumption, on the other hand, is based on the use of electricity per unit of fuel generated (e.g., kWh of electricity used to process one metric ton or 124.7 Nm^3 of natural gas). With more than 50% of the total electricity production stemming from fossil fuels in most countries, the approach here takes into account the regional energy mix (relation of electricity production generated with fossil fuels versus RES). The electricity consumption is converted into used fuel by multiplying the needed electrical energy with the conventional efficiency of the plant, where that electricity was generated, and the fuel mix assumed in that country (second part of the right side of Equation (1)).

$$Cons = \frac{1}{Comb_k}\left(\sum_n \left[Comb_{cons}\cdot LHV_{comb,c}\right] + Elec_{cons}\cdot\left[A\cdot\frac{1}{\eta_{pplant}} + (1-A)\cdot E_{mix,p}\cdot\frac{1}{\eta_{pplant,a}}\right]\right) \tag{1}$$

Where:

- A is a constant that takes the value of 1 if the consumed electricity is generated in a fossil fuel power plant and 0 otherwise.
- $Comb_{cons}$ is the mass of the fuel required to process the wished fuel ($Comb_k$), expressed in tons.
- $Comb_k$ is the mass flow of processed fuel, expressed in metric tons (124.7 Nm^3 in the case of natural gas).
- $Elec_{cons}$ is the consumed electricity in the analyzed stage, expressed in MJ.
- $E_{mix,p}$ is the percentage of electricity obtained from fossil fuels in country *p*.
- $LHV_{comb,c}$ is the lower heating value (LHV) of the used fuel, expressed in MJ/ton.
- n is the number of fuels used during the processing of $Comb_k$.
- η_{pplant} is the conventional efficiency of the fossil fuel plant that generates the required electricity, without units.
- $\eta_{pplant,a}$ is the average conventional efficiency of fossil fuel power plants in country *p*, without units.

As seen, to calculate the total energy consumption with Equation (1) requires the knowledge of several inputs. If some of these inputs are not known, approximate or mean values could be used.

Equation (1) can be further adapted to each analyzed stage and characteristics, such as pipeline or tanker transportation. For belt conveyors, the energy consumption is calculated in MJ/t as follows:

$$Cons_{belt} = \frac{1}{Comb_{transp}}\cdot Elec_{cons}\cdot\left(A\cdot\frac{1}{\eta_{pplant}} + (1-A)\cdot E_{mix,p}\cdot\frac{1}{\eta_{pplant,a}}\right) \tag{2}$$

Where:

- $Comb_{transp}$ is the mass of transported fuel, expressed in metric tons.

The energy consumption of lorry transportation is estimated in MJ/t with Equation (3):

$$Cons_{truck} = \frac{1}{Comb_{transp}}\cdot Cons_{km}\cdot\rho_{comb,m}\cdot LHV_{comb,m}\cdot D \tag{3}$$

Where:

- $Cons_{km}$ is the fuel consumption of the truck, expressed in liters per kilometer.
- D is the distance the fuel is transported, expressed in kilometers.
- $LHV_{comb,m}$ is the LHV of the fuel used to power the lorry, expressed in MJ/ton.
- $\rho_{comb,m}$ is the density of the fuel used to power the lorry, expressed in tons/m^3.

The energy consumption of pipeline transportation can be expressed in several ways. Equation (4) accounts for the number of compressor stations, the number of compressors in them and their electric consumption. Equation (5) is based on Dones et al. (2007) and calculates the energy requirement based on the amount of fuel transported, as a percentage of its energy content. Finally, Equation (6) approximates the energy consumption of pipeline transportation when information needed for Equations (4) and (5) is not known or is very complicated to estimate.

$$Cons_{pipe} = \frac{1}{Comb_{transp}\cdot\rho_{comb}}\cdot\frac{n_C\cdot P_C}{\dot{V}}\cdot\frac{D}{R_{station}}\left(A\cdot\frac{1}{\eta_{pplant}} + (1-A)\cdot E_{mix,p}\cdot\frac{1}{\eta_{pplant,a}}\right) \tag{4}$$

$$Cons_{pipe} = \frac{1}{Comb_{transp,t}\cdot\rho_{comb}}\cdot\dot{V}\cdot X_{comb}\cdot D\cdot LHV_{comb,c} \tag{5}$$

$$Cons_{pipe} = \frac{D}{R_{station}}\cdot Elec_{cons}\cdot\left(A\cdot\frac{1}{\eta_{pplant}} + (1-A)\cdot E_{mix,p}\cdot\frac{1}{\eta_{pplant,a}}\right) \tag{6}$$

Where:

- $Comb_{transp}$ is the volume of the transported fuel, expressed in m^3.
- $Comb_{transp,t}$ is the volumetric flow rate of transported fuel, expressed in m^3/s.
- $LHV_{comb,m}$ is the LHV of the fuel used to power the lorry, expressed in MJ/ton.
- n_C is the number of compressor stations along the pipeline, without units.
- P_C is the power required by the compressors of the compression stations, expressed in MW.
- $R_{station}$ is the distance between compression stations, (64–160 km according to (MECF, 2021)), expressed in kilometers.
- t is the monitored time, expressed in seconds.
- $\dot{V}$ is the volumetric flow of the transported fuel, expressed in m^3/s.
- X_{comb} is the parts per unit of fuel necessary to perform the fuel transport per unit of distance ((0.018/1000 km in Europe according to (Dones et al., 2007)), expressed in km-1.
- ρ_{comb} is the density of the transported fuel, expressed in metric tons/m^3.

The energy requirement for rail transportation can be estimated in MJ/t with Equation (7):

$$Cons_{ferro} = \frac{1}{Comb_{transp}}\cdot\left(Cons_{km}\cdot\rho_{comb,m}\cdot LHV_{comb,m}\cdot D + Elec_{cons}\cdot\left[A\cdot\frac{1}{\eta_{pplant}} + (1-A)\cdot E_{mix,p}\cdot\frac{1}{\eta_{pplant,a}}\right]\right) \tag{7}$$

Finally, the energy consumption of maritime transport can be estimated in MJ/t as follows:

$$Cons_{sea} = \frac{1}{Comb_{transp}} \cdot Cons_{km} \cdot \rho_{comb,m} \cdot PCI_{comb,m} \cdot D \tag{8}$$

The total energy consumption of the fuel is estimated by adding the energy consumption of the different preparation stages. This total energy consumption is included in the denominator of the efficiency (required fuel input) to calculate the total efficiency:

$$\eta_a = \frac{\dot{W}_{NET}}{Fuel_{input} + Fuel_{ac+trans}} = \frac{\dot{W}_{NET}}{\dot{Q}_{IN} + \dot{m}_{comb} \cdot Cons_{total}} \tag{9}$$

With, $Fuel_{input} = \dot{m}_{comb} \cdot LHV_{comb}$ and $Fuel_{ac+trans} = \dot{m}_{comb} \cdot \ (Cons_{ext} + Cons_{proc} + Cons_{trans})$. $\dot{m}_{comb}$ stands for the mass flow rate of the fuel used in the power plant and $Cons_{ext}$, $Cons_{proc}$ and $Cons_{trans}$ stand for the energy input required at the stages of extraction, processing, and transportation, respectively.

The impact of the preparation steps of fossil fuels on the total efficiency of power plants is studied using two case studies in Spain. To further understand the impact of the preparation stages on the total efficiency, a sensitivity analysis is consequently carried out. The focus of the sensitivity analysis are the parameters $\mathrm{Comb}_{\mathrm{cons}} + \mathrm{Elec}_{\mathrm{cons}}$, defined as a unique parameter ($\mathrm{Comb}_{\mathrm{k}}$), and the transportation distance. The default values for the parameters are varied within a specified range and their impact is then evaluated by studying the change of the total efficiency.

3. Case studies

The energy consumption of extraction, processing and transportation varies from case to case and from one part of the world to another. For example, the energy consumption of transportation is particularly important for non-producing countries, like Spain, that import most of the fuel they need. This is especially true today that coal mines are being decommissioned (Planelles, 2018). Two case studies are used here to reveal the impact of the studied parameters on the total efficiency. Required data on the used case studies is mainly gathered through personal communications with the personnel of the power plants and other public sources. Other unknown data is derived from LCA studies found in literature and appropriately cited here.

3.1. Case study 1

The first case study is the combined-cycle power plant of Sabón (CCPP Sabón onwards). The power plant is located in the Industrial Estate of Sabón, in the town of Arteixo, A Coruña, northern Spain. Its exact location is 43° 19′ 55″ N, 8° 30’ 00″ O, in horizontal coordinates. Originally the plant included two oil-fueled plants of 120 MW and 350 MW (Groups I & II). In 2008, a natural-gas powered combined-cycle unit (Group III) of 400 MW was put into operation. With the oil plants decommissioned in 2011, only the natural-gas part is in operation today. The power plant has a single-axis configuration, with the gas and vapor turbines joined on the same axis and connected to a unique electric generator. This is a cheap and effective configuration that reduces the engineering costs (FACET, 2014). The power plant uses a 9FA gas turbine from General Electric, a steam turbine working with low-, medium-, and high-pressure levels, an electric generator, a burner, and a condenser. According to Red Eléctrica Española, in 2019 the plant had a net electricity production of 1548 GWh with 5807 h of operation and a capacity factor of 46.3% (REE, 2020).

The natural gas used in the power plant comes from the Zohr gas field, located in the Mediterranean Sea near the coast of Egypt. This field has a surface of 100 km^2, a daily production of 76.46 hm^3 and potential natural gas reserves of up to 850 km^3 (Eni, 2020). After extraction, the fuel is processed in the field installations, and transported to the Damieta port with a pipeline. There, it is liquefied to facilitate transport. Two liquified natural gas (LNG) carriers are mainly used for transport: The Galicia Spirit, with a capacity of 140,500 Nm^3; and the Cádiz Knutsen, with a capacity of 135,240 Nm^3. The fuel travels 4700 km by sea, with destination the port of Ferrol. The fuel is regasified there in the *regasificadora* Reganosa and is sent to the power plant with a pipeline. The gas then travels another 40,583 m at 80 bars and at a maximum volumetric flow of 106 Nm^3/h. The pipeline does not include a compression station.

Table 1
Energy consumption of natural gas preparation.

Stage	Value	Reference
Extraction	12.8773 MJ/m^3 NG 20–30 m^3 diesel/d Electrical installation: 500 MW Electrical installation: 25 MW Electrical installation: 5.5 MW	A. Riva et al. (Riva et al., 2006) IPIECA (IPIECA, 2013) Jørgen Chr. Myhre (Myhre, 2001) T. Nguyen et al. (van Nguyen et al., 2016)
Processing at gas field	96.52 MMBTU/h per 100 MMscfd 1613 MMBTU/h per 600 MMscfd 12.64 MW per 14 MMSm^3/d 2.2 MW per 7.6 MMSm^3/d	L. Khoshnevisan et al. (Khoshnevisan et al., 2021) Arthur J. Kidnay et al. (Kidnay et al., 2011)
Gas field – Damieta pipeline transport	Volumetric Flow: (14.157–792.872) dam^3/d Operative pressure: 16.55–327.50 bar	Gasprocessingnews.com(Rabbeea and Abdel-Waly, 2018)
Liquefaction	2900 MJ/t	A. Franco y C. Casarosa (Franco and Casarosa, 2014)
Damieta – Ferrol tanker transport	0.49 MJ/t (HFO) 0.50 MJ/t (MGO) 0.52 MJ/t (LNG)	S. Bengtsson et al. (Bengtsson et al., 2011)
Regasification	800 MJ/t	A. Franco y C. Casarosa (Franco and Casarosa, 2014)
Ferrol – CCPP Sabón pipeline transport	Pipeline diameter: 16” Operative pressure: 80 bar % Fuel used for transport: 1.8E-05 km^{-1}	BOE núm. 276 (Ministerio de Administraciones Públicas, 2004)

Table 2
Energy consumption of coal preparation.

Stage	Value	Reference
Extraction	365.81 MJ_{l}/t 50.04 $\mathrm{MJ}_{\mathrm{elec}}$/t 43.7576 $\mathrm{kWh}_{\mathrm{e}}$/t 0.0698 $\mathrm{GJ}_{\mathrm{heat}}$/t 21.3 kWh/t 1.3E-04 $\mathrm{t}_{\mathrm{diesel}}$/t 2.54E-05 $\mathrm{t}_{\mathrm{gasoline}}$/t 3.88E-03 $\mathrm{t}_{\mathrm{coal}}$/t	R. Dones et al. (Dones et al., 2007) Dorota Burchart-Korol et al. (Burchart-Korol et al., 2016) D. Mu y C. Wang (Mu and Wang, 2015)
Processing at mine facilities	174.6 $\mathrm{MJ}_{\mathrm{elect}}$/t 9.2348 kWh/t 32.4 $\mathrm{MJ}_{\mathrm{elect}}$/t	R. Dones et al. (Dones et al., 2007) Dorota Burchart-Korol et al. (Burchart-Korol et al., 2016) D. Mu y C. Wang (Mu and Wang, 2015)
Internal belt conveyor transport	Transport capacity: 1000 t/h Electrical power: 57 kW	J. Ji et al. (Ji et al., 2020)
Mine – Durban freight train transport	0.9–1.2 kWh/t-km	García-Álvarez et al. (Garcia-Alvarez et al., 2013)
Durban – Tarragona bulk carrier transport	0.49 MJ/t (HFO) 0.50 MJ/t (MGO) 0.52 MJ/t (LNG)	S. Bengtsson et al. (Bengtsson et al., 2011)
Tarragona – Alcudia bulk carrier transport	0.49 MJ/t (HFO) 0.50 MJ/t (MGO) 0.52 MJ/t (LNG)	S. Bengtsson et al. (Bengtsson et al., 2011)
Alcudia – Es Murterar truck transport	34.5 l diesel/100 km	Ministerio de Fomento (Ministerio de Transportes, 2020)

Table 3
Energy consumption at each preparation stage of the two case studies.

Case Study 1		Case Study 2	
Stage	Energy consumption (MJ/t)	Stage	Energy consumption (MJ/t)
Extraction	23398.96 (Riva et al., 2006)	Extraction	524.12 (Dones et al., 2007)
	0.13 (IPIECA, 2013)		464.31 (Dones et al., 2007)
	0.20 (IPIECA, 2013)		672.13 (Burchart-Korol et al., 2016)
	21.12 (Myhre, 2001)		577.95 (Burchart-Korol et al., 2016)
	1.06 (van Nguyen et al., 2016)		356.15 (Mu and Wang, 2015)
	0.23 (van Nguyen et al., 2016)		264.50 (Mu and Wang, 2015)
Processing at gas field	2181.85 (Khoshnevisan et al., 2021)	Processing at mine facilities	552.36 (Dones et al., 2007)
	6067.04 (Khoshnevisan et al., 2021)		343.69 (Dones et al., 2007)
	196.88 (Kidnay et al., 2011)		105.17 (Burchart-Korol et al., 2016)
	63.12 (Kidnay et al., 2011)		65.44 (Burchart-Korol et al., 2016)
Gas field – Damieta pipeline transport	139.13 ("Flow assurance study of gathering, 2018)		102.50 (Mu and Wang, 2015)
Liquefaction	5438.1 (Franco and Casarosa, 2014)		63.78 (Mu and Wang, 2015)
Damieta – Ferrol tanker transport	2303.00 (Bengtsson et al., 2011)	Internal belt conveyor transport	0.55 (Ji et al., 2020)
	2350.00 (Bengtsson et al., 2011)	Mine – Durban freight train transport	2052.00 (Garcia-Alvarez et al., 2013)
	2444.00 (Bengtsson et al., 2011)	Durban – Tarragona bulk carrier transport	5576.20 (Bengtsson et al., 2011)
Regasification	800.00 (Franco and Casarosa, 2014)		5690.00 (Bengtsson et al., 2011)
Ferrol – CCPP Sabón pipeline transport	40.00 (Ministerio de Administraciones Públicas, 2004)		5917.60 (Bengtsson et al., 2011)
		Tarragona – Alcudia bulk carrier transport	106.17 (Bengtsson et al., 2011)
			108.34 (Bengtsson et al., 2011)
			112.67 (Bengtsson et al., 2011)
		Alcudia – Es Murterar truck transport	4.09 (Ministerio de Transportes, 2020)

Table 4
Variation of the total efficiency of Case Study 1 (CCC Sabón), relative to its base value of 48.15%.

Subcase	Total efficiency range [%]	Difference between reference efficiency and maximum total efficiency [%]	Difference between reference efficiency and minimum total efficiency [%]	Max – Min total efficiency ratio	Subcase reference [MJ/t]
1	28.3–30.3	– 37.1	– 41.2	1.0706	23398.96 (Riva et al., 2006)
2	37.8–41.4	– 14.0	– 21.5	1.0966	0.13 (IPIECA, 2013)
3	37.8–41.4	– 14.0	– 21.5	1.0966	0.20 (IPIECA, 2013)
4	37.8–41.4	– 14.0	– 21.5	1.0966	21.12 (Myhre, 2001)
5	37.8–41.4	– 14.0	– 21.5	1.0966	1.06 (van Nguyen et al., 2016)
6	37.8–41.4	– 14.0	– 21.5	1.0966	0.23 (van Nguyen et al., 2016)

3.2. *Case study 2*

The second case study is the thermal power plant of Es Murterar. The power plant is located in the town of Alcudia, Mallorca, Balearic Isles. Its exact location is 39° 48′ 35″ N, 03° 05’ 42″ E, in horizontal coordinates. Es Murterar was initially equipped with four steam cycles driven by black coal and two gas-turbine cycles driven by gasoil. The two coal-powered units, that came into operation in 1981 and 1982, had a nominal power of 125 MW and 350 MW and an average conventional efficiency of 35.71%. In 2018, one year before being decommissioned, the coal-fueled parts produced 2392 GWh of electricity (REE, 2019). This example is used here as an indicative coal-based plant for the testing of the concept of the total efficiency.

The bituminous or black coal used for power generation at Es Murterar is extracted from underground mines in South Africa, in the province of Mpumalanga. The coal is transported with a belt conveyor for processing in the mine facilities. Once the coal is processed, it is loaded onto a freight train that carries the fuel 475 km to the city of Durban and its port. As the carrier has a bigger draft than the port in Alcudia allows, the coal is shipped inside a bulk carrier to the port of Tarragona, on the eastern coast of Spain. From Tarragona, a smaller carrier with a capacity of 3000 tons transports the fuel to Alcudia, where it is unloaded and sent to the power plant using a dump, travelling 8.1 km.

4. Results and discussion

Tables 1 and 2 present published data on each step of the life cycle of the fuels used in this work. The energy consumption at each stage of fossil fuel preparation for the two case studies evaluated here is presented in Table 3. The energy requirement of each individual stage is calculated using the reported data with the equations shown in Methods. Distinct values from different sources have been accounted for in separate scenarios (see Appendix B).

The scenarios defined include all of the alternative values shown in Tables 2 and 3. A total of 72 scenarios of energy consumption for Case Study 1 (CCPP Sabón) and 324 scenarios for Case Study 2 (Es Murterar) have been specified. For example, the first scenario for Es Murterar power plant uses the energy requirement of the extraction stage and processing in the mine facilities from the work of R. Dones et al. (2007), the calculation of Ji et al. (2020) for internal belt conveyor transportation, the estimate of García-Álvarez et al. (2013) for freight train transport, the HFO consumption for both stages of bulk carrier transport from S. Bengtsson et al. (2011), and, finally, the consumption of dump truck average road consumption from the Ministerio de Fomento (Ministerio de Transportes, 2020). The scenarios are then grouped into six subcases based on the reference used for the extraction of the fuel. For example, all subcases using the work of Dones et al. (2007) are

Table 5
Variation of the total efficiency of Case Study 2 (Es Murterar), relative to its base value of 35.71%.

Subcase	Total efficiency range [%]	Difference between reference efficiency and maximum total efficiency [%]	Difference between reference efficiency and minimum total efficiency [%]	Max – Min total efficiency ratio	Subcase reference [MJ/t]
1	26.7–27.3	– 23.53	– 25.27	1.0232	524.12 (Dones et al., 2007)
2	26.8–27.4	– 23.33	– 25.08	1.0233	464.31 (Dones et al., 2007)
3	26.8–27.4	– 23.22	– 24.97	1.0233	672.13 (Burchart-Korol et al., 2016)
4	26.8–27.5	– 23.09	– 24.84	1.0234	577.95 (Burchart-Korol et al., 2016)
5	26.9–27.5	– 22.87	– 24.64	1.0234	356.15 (Mu and Wang, 2015)
6	27.0–27.6	– 22.66	– 24.44	1.0235	264.50 (Mu and Wang, 2015)

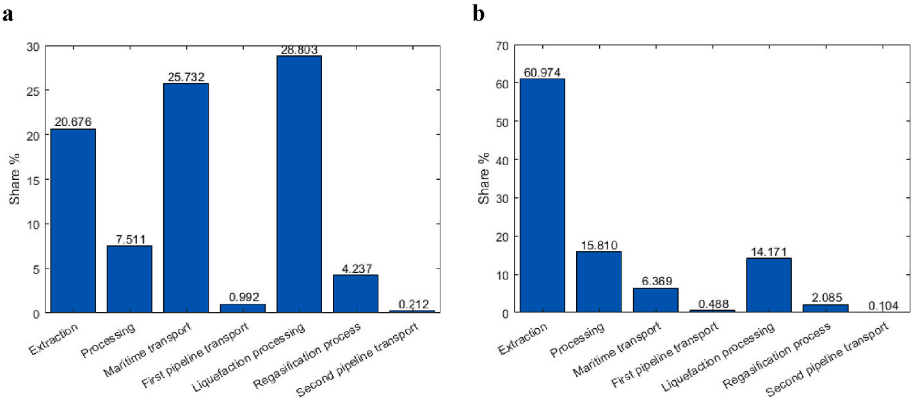

Fig. 1. Contribution of the different processes in the overall energy consumption (**a**) and the example of Subcase 1 (**b**) of the CCPP Sabón power plant.

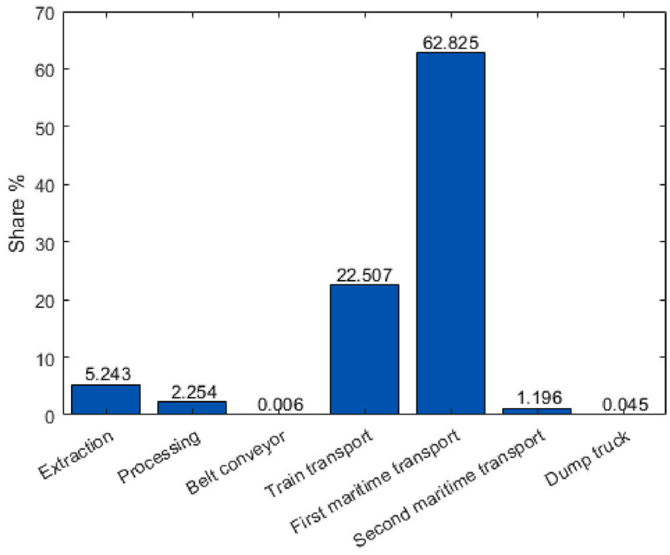

Fig. 2. Contribution of the different processes in the overall energy consumption of the Es Murterar power plant.

grouped together (Subcase 1). In each subcase, the extreme values determine the possible range of the results with a maximum and minimum total efficiency. The total efficiencies of every subcase are shown in Tables 4 and 5. The difference between the maximum and minimum total efficiencies of the subcases of CCPP Sabón (see Table 4) is due to the range of energy consumption needed at the extraction stage made by Riva et al. (2006).

Table 6
Average energy consumption of each lifecycle stage of natural gas and coal.

Fuel	Stage	Average energy consumption [MJ/t]	Fuel	Stage	Average energy consumption [MJ/t]
Natural gas	Extraction	3.90E+03	Coal	Extraction	4.78E+02
	Processing	1.41E+03		Processing	2.05E+02
	Maritime transport	4.57E+03		Belt conveyor	5.51E-01
	1st pipeline transport	1.87E+02		Train transport	2.05E+03
	Liquefaction	5.44E+03		1st maritime transport	5.73E+03
	Regasification	8.00E+02		2nd maritime transport	1.09E+02
	2nd pipeline transport	4.00E+01		Truck transport	4.09E+00

The conventional efficiencies of the two case studies, used for comparison purposes in Tables 4 and 5, are 48.15% and 35.71% for the natural gas and the coal plants, respectively. Reported efficiencies of natural gas combined-cycle power plants are between 45 and 57% and efficiencies of coal-fired power stations are in average 33% worldwide, 38.6% in China and 41.6% in Japan (POWER, 2017), while state of the art coal plants are reported to reach efficiencies of 40–50% (Storm, 2020; Hitchin, 2018). The two conventional efficiencies are thus seen to be within the range of efficiencies of other existing power plants using similar technology.

As seen in Table 4, the total efficiency of Case Study 1 in the most conservative scenario is 14% lower than the conventional efficiency and 41.2% lower in the worst-case scenario. The latter corresponds to

Table 7
Sensitivity analysis: Distance of coal transportation.

Subcase N°	Maximum efficiency percentage change					
	−50%	−25%	25%	50%	75%	100%
Subcase 1	12.324	5.804	−5.201	−9.887	−14.132	−17.995
Subcase 2	12.359	5.820	−5.213	−9.910	−14.163	−18.032
Subcase 3	12.380	5.829	−5.220	−9.923	−14.181	−18.054
Subcase 4	12.402	5.657	−5.375	−10.070	−14.320	−18.188
Subcase 5	12.440	5.371	−5.631	−10.313	−14.552	−18.409
Subcase 6	12.479	5.080	−5.891	−10.560	−14.788	−18.634
Subcase N°	Minimum efficiency percentage change					
	−50%	−25%	25%	50%	75%	100%
Subcase 1	12.037	5.677	−5.098	−9.701	−13.879	−17.687
Subcase 2	12.072	5.692	−5.111	−9.724	−13.910	−17.725
Subcase 3	12.092	5.701	−5.118	−9.737	−13.928	−17.747
Subcase 4	12.115	5.525	−5.276	−9.888	−14.071	−18.162
Subcase 5	12.153	5.233	−5.538	−10.137	−14.309	−18.212
Subcase 6	12.191	4.936	−5.805	−10.391	−14.551	−18.342

Table 8
Sensitivity analysis: Coal energy consumption.

Subcase N°	Maximum efficiency percentage change					
	−50%	−25%	25%	50%	75%	100%
Subcase 1	1.690	0.838	−0.824	−1.635	−2.433	−3.217
Subcase 2	1.562	0.775	−0.763	−1.515	−2.255	−2.985
Subcase 3	1.489	0.739	−0.728	−1.446	−2.153	−2.851
Subcase 4	1.408	0.699	−0.689	−1.369	−2.040	−2.701
Subcase 5	1.272	0.632	−0.624	−1.241	−1.849	−2.451
Subcase 6	1.134	0.564	−0.558	−1.109	−1.654	−2.194
Subcase N°	Minimum efficiency percentage change					
	−50%	−25%	25%	50%	75%	100%
Subcase 1	1.033	0.514	−0.509	−1.012	−1.510	−2.004
Subcase 2	0.902	0.449	−0.445	−0.886	−1.323	−1.757
Subcase 3	0.827	0.412	−0.408	−0.814	−1.216	−1.614
Subcase 4	0.744	0.370	−0.368	−0.733	−1.095	−1.455
Subcase 5	0.605	0.302	−0.300	−0.598	−0.894	−1.188
Subcase 6	0.464	0.231	−0.230	−0.460	−0.688	−0.915

Table 9
Sensitivity analysis: Distance of natural gas transportation.

Subcase N°	Maximum efficiency percentage change					
	−50%	−25%	25%	50%	75%	100%
Subcase 1	1.455	0.722	−0.712	−1.414	−2.106	−2.788
Subcase 2	1.952	0.967	−0.948	−1.879	−2.792	−3.689
Subcase 3	1.953	0.967	−0.949	−1.879	−2.793	−3.690
Subcase 4	1.953	0.967	−0.949	−1.879	−2.793	−3.690
Subcase 5	1.953	0.967	−0.949	−1.879	−2.793	−3.690
Subcase 6	1.953	0.967	−0.949	−1.879	−2.793	−3.690
Subcase N°	Minimum efficiency percentage change					
	−50%	−25%	25%	50%	75%	100%
Subcase 1	1.476	0.733	−0.722	−1.434	−2.135	−2.827
Subcase 2	2.029	1.005	−0.985	−1.950	−2.897	−3.826
Subcase 3	2.030	1.005	−0.985	−1.951	−2.898	−3.827
Subcase 4	2.030	1.005	−0.985	−1.951	−2.898	−3.827
Subcase 5	2.030	1.005	−0.985	−1.951	−2.898	−3.827
Subcase 6	2.030	1.005	−0.985	−1.951	−2.898	−3.827

Table 10
Sensitivity analysis: Natural gas energy consumption.

Subcase N°	Maximum efficiency percentage change					
	−50%	−25%	25%	50%	75%	100%
Subcase 1	18.794	8.590	−7.330	−13.659	−19.179	−24.036
Subcase 2	4.564	2.231	−2.136	−4.182	−6.144	−8.028
Subcase 3	4.549	2.224	−2.129	−4.170	−6.127	−8.006
Subcase 4	4.549	2.224	−2.129	−4.169	−6.126	−8.005
Subcase 5	4.549	2.224	−2.129	−4.169	−6.126	−8.005
Subcase 6	4.549	2.224	−2.129	−4.169	−6.126	−8.005
Subcase N°	Minimum efficiency percentage change					
	−50%	−25%	25%	50%	75%	100%
Subcase 1	15.589	7.231	−6.317	−11.884	−16.826	−21.244
Subcase 2	0.066	0.033	−0.033	−0.066	−0.099	−0.132
Subcase 3	0.050	0.025	−0.025	−0.050	−0.076	−0.101
Subcase 4	0.050	0.025	−0.025	−0.050	−0.075	−0.100
Subcase 5	0.050	0.025	−0.025	−0.050	−0.075	−0.099
Subcase 6	0.050	0.025	−0.025	−0.050	−0.075	−0.099

Subcase 1 that considers the worst-case (maximum) energy consumption of each preparation stage. In Subcase 1 the energy consumption of the extraction stage is much higher than in the other subcases. The other scenarios result in total efficiencies in the order of 21.5% lower than the conventional one, still a significant relative reduction. On the other hand, the comparison between total and conventional efficiencies is more balanced between the remaining subcases. This can be observed in Table 5, where it is seen that the total efficiency of Case Study 2 decreases between 22.66% and 25.27%.

Figs. 1 and 2 present the contribution of the different stages to the overall energy consumption of the fossil fuel preparation. These are based on the average energy consumption values of all subcases for each power plant (Table 6). The large impact of the extraction based on Riva et al. (2006) is best illustrated with Subcase 1 of the CCPP Sabón plant, shown on panel (b) of Fig. 1. The liquefaction process of the gas is, on average, the greatest contributor to the final energy consumption of natural gas processing, followed by maritime transport and extraction. On the other hand, maritime and freight train transportation are seen to be the largest contributors to the coal's total energy consumption.

To complete the analysis, a sensitivity analysis is performed to study the impact of the transportation distance and the efficiency of the machinery used on the total efficiency. The values of energy consumption of Table 3 are varied from −50% to +100% with intervals of 25 percentage points. This range was chosen to show probable changes in the consumption of fossil fuels throughout the plant's life cycle, such as improvements on technology, that could potentially reduce their use; or obstacles encountered during the preparation processes. The results are shown in Tables 7 and 8 for coal, and Tables 9 and 10 for natural gas. In these tables, each subcase represents a combination of values of Table 3. Each subcase uses one value from each stage, that is, one value of extraction, one of processing, etc. The combinations of each power plant (72 for NG and 324 for coal) are then grouped based on the extraction stage considered (for *Subcase 1*, case 1 of the extraction stage (*Ext*$_1$) is used for *Subcase 2*, case 2 (*Ext*$_2$) and so on, until *Subcase 6)*. Additional explanations can be found in Appendix B.

Some data overlap is observed when similar estimates are reported in different reports. Here, a 0% change means that the estimated efficiency is equal to the base total efficiency (Tables 4 and 5). As expected, when the energy consumption increases (with a greater positive percent change), the total efficiencies of the plants decrease. The opposite is true with decreasing energy consumption. The total efficiency in that case increases strongly. The same trend is seen for changes in the transport distance.

Tables 7 and 8 show how energy consumption and transportation distance affect the total efficiency of the coal power plant. The variation of the energy consumption of the different stages, namely extraction, processing, and belt conveyor transportation (Table 7), result in larger deviations between the different scenarios than transport distances (Table 8). For example, a doubling of the energy consumption (increase by 100%) will result in the minimum total efficiency of Subcase 1, 2.27% lower than that of Subcase 6 of the same scenario. This difference when the transportation distance is doubled (increase by 100%), is 0.97%. However, it is obvious that the impact of the transport distance on the total efficiency is much stronger.

Tables 9 and 10 show the results of the sensitivity analysis of the natural gas plant. It is seen that the changes in maximum and minimum total efficiencies are significant when the transportation distance is varied. The transportation has thus a much higher impact on the overall energy requirement of the preparation steps, when compared to the energy consumption of the remaining preparation steps (Figs. 1 and 2). The energy contribution of each preparation stage of Case Study 1 is shared among the different parameters in a more equal manner than in Case Study 2. This is why the total efficiency presents similar deviations from the base value in the case of CCPP Sabón. On the other hand, coal, the major energy contributor in the case of Es Murterar, has a much longer transportation route, and the energy consumption is linearly dependent on it. In this case thus, the increase of the transportation energy consumption impacts the total efficiency greatly.

It is noted that transportation distance plays a major role in the final energy consumption of both coal and natural gas plants. Specifically in coal plants, when the transportation distance doubles, the total efficiency decreases by almost 20%. It becomes obvious thus that countries that need to import most of their required fuel are significantly affected from this issue. Spain is such a case, and the total efficiency of both case studies used here are dominated by high transportation penalties.

5. Conclusions

This paper defined the concept of total efficiency that incorporates the energy requirement of the preparation stages (i.e., extraction, processing, and transportation) of fossil fuels into the concept of conventional efficiency. Total efficiency uses life cycle assessment analyses to estimate the additional energy requirements of each preparation stage of the fuels. The energy requirement of each preparation stage is then linked to additional fuel and introduced into efficiency. Two case studies of real power plants have been used to test the developed concept. These applications can be seen as a guide on how to use the developed equations, as well as examples of the impact fossil fuel preparation may exert on the evaluation of fossil fuel plants and their comparison dynamics with other kinds of power plants.

It has been shown that accounting for the preparation steps of fossil fuels affects the power plant efficiencies significantly. The impact of each step on the final energy consumption depends on the type of fuel and the different conditions of each step and regional characteristics and requirements. It was seen that the total efficiency dropped by 14% to 41% when extraction, processing, and transportation of fossil fuels was included. Looking at the individual parameters, transportation was found to be one of the most decisive parameters, able to reduce the total efficiency of coal plants up to 20% when the distance is doubled. In addition, the extraction stage of coal and liquefaction of natural gas were also seen to have a strong effect, when compared to other preparation steps. Overall, it is seen that the inclusion of the preparation steps in the life cycle of fossil fuels decreases the efficiency of the power plants significantly as well. This consideration can play an important role in the path towards energy sustainability, as better solutions can only be identified by well-balanced and fair tools.

CRediT authorship contribution statement

Fontina Petrakopoulou: Supervision, Conceptualization, Methodology, Writing – original draft, Review & Editing. **Enrique García-Tenorio Corcuera:** Methodology, Analysis, Writing – original draft, Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

Fontina Petrakopoulou would like to thank the Spanish Ministry of Science, Innovation and Universities, and the Universidad Carlos III de Madrid (Ramón y Cajal Programme, RYC-2016-20971).

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.133409.

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