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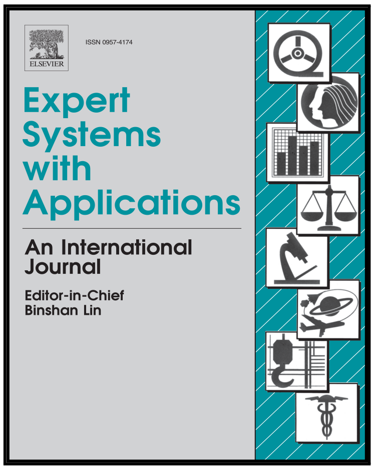

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Highlights

- AHP applied to sustainable supply chain development in the renewable energy sector.
- The AHP model takes into account both logical and quantitative information.
- The proposed approach provides decision makers with main factors and sub-criteria.
- Main European countries producers of PV energy are compared.
- Results agree with the PV development in the period 2000-2017 in these countries.

An AHP-based multi-criteria model for sustainable supply chain development in the renewable energy sector

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Abstract

The aim of this paper is to provide a multi-criteria decision making framework based on the Triple Bottom Line principles and Analytic Hierarchy Process methodology for sustainable supply chain development in the renewable energy sector. The proposed framework encompasses the whole energy production supply chain, from raw materials' suppliers to disposal. In particular, the photovoltaic energy sector has been used as case study and represents the focus of this work. The framework is based on the three Triple Bottom Line dimensions such as social, economic and environmental. Furthermore, literature review and expert opinions are used to identify and assess the sub-criteria for each dimension, followed by pair-wise comparison. Finally, the proposed framework is used to evaluate the seven European countries that conjointly represent the 86.8% of the total photovoltaic installed capacity in Europe, using both logical and quantitative information. Results are in agreement with the photovoltaic development in the period 2000-2017 in these countries. The proposed frame-

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work provides the decision makers with a powerful tool for making sustainable investment decisions in the photovoltaic energy sector.

Keywords: Analytic Hierarchy Process, Multi-criteria decision making, Photovoltaic sector, Renewable energy, Sustainable supply chain, Triple Bottom Line

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1. Introduction

The use of fossil energy around the world is one of the main reasons for global warming. In the last decade, many efforts have been made in order to promote the production and use of renewable energy (RE). Some policies like the Kyoto Protocol (United Nations, 1998) and the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC, 2014) have been put in place in order to enhance energy efficiency and to promote the use of more sustainable energy sources. Moreover, measures aimed at the reduction of CO_2 emissions have been adopted by the European Union (European Parliament, 2009, 2012b). In particular, *Europe 2020* (European Commission, 2010b) is one of the most important strategies for mitigating the greenhouse gas emissions.

It is now well accepted that the economic, technological, social, and political development requires to intensify the deployment of both sustainable and diverse energy (Streimikiene et al., 2012), leading to the use of more efficient renewable energy sources (RES) while decreasing the use of fossil energy. In such a context, photovoltaic (PV) energy currently plays a fundamental role and its importance is expected to grow (European Commission, 2017).

The cumulative installed solar PV power reached 398 GW by the end of 2017, being 113.2 GW the total installed PV capacity in Europe (Solar Power Europe, 2019). From 2010 to 2017, the total global PV capacity jumped over 970% from less than 41 GW and, looking back ten years, the PV market grew more than 80 times from 5 GW of the total commissioned PV capacity at the end of 2005. The total share reached 12.1% of total global power output in 2017

(Solar Power Europe, 2019). Although the total installed capacity in Europe represents around 28.4% of the total PV potential in the world, 86.8% of this is located in seven countries only: Germany, Italy, the United Kingdom, France, Spain, Belgium and Greece. These countries are used as case study in this research.

Although PV energy is beginning to play an important role in power generation in many countries, it is well known that some mistakes have been made in the adoption of this RE. In fact, the application of policies to promote the use of PV energy has caused significant imbalances in electricity systems and distortion of electricity prices in some countries (Avril et al., 2012; Honrubia-Escribano et al., 2018; Pyrgou et al., 2016; Ramírez et al., 2017). Furthermore, the Triple Bottom Line (TBL) principles (Elkington, 1997), based on the economic, social and environmental pillars of sustainability, have put pressure on governments and businesses to achieve environmental and social sustainability, in addition to the traditional economic dimension. Therefore, more effective decision making processes including environmental and social aspects that go beyond the mere economic perspective are required in the current context, which can be achieved by putting the TBL principles into practice.

The photovoltaic supply chain (PVSC) involves all activities related to the transformation flows of materials and energy from raw materials, through suppliers, photovoltaic system assemblers, distributors and end users or consumers, to the recovery or disposal of power plants, as well as the associated information flows. Material, energy and information flows go up and down the PVSC. It is different from the SCs of consumer or industrial goods mainly because of its contribution to energy conservation and Green House Gas (GHG) emission reduction, and also because it is capital- and technology-intensive with a very high entry barrier, and its construction and operation is not possible without governments implementing appropriate industry and facilitation policies (Chen and Su, 2014). Therefore, making sustainable decisions in the PV sector is challenging because of the many factors involved along the PVSC, from raw material suppliers to disposal, affecting all the SC stages.

In the literature, several authors have taken into account economic, environmental, and social factors in the development of RES (Cucchiella et al., 2017; Govindan et al., 2013; Streimikiene et al., 2012) and the assessment of RE from a SC perspective (Cucchiella and D'Adamo, 2013; Davies and Joglekar, 2013; Wee et al., 2012). Considering the different factors involved in the decision making process at every stage in the SC, it represents a complex multi-criteria decision making (MCDM) problem (Uygun and Dede, 2016).

MCDM frameworks have been used in recent years to resolve different problems concerning RE, many of them in the PV context. Section 2 presents a detailed literature review of the most significant works about it. Three types of decisions mainly have been addressed: choosing the most suitable production site location, the best technology and the most appropriate RE policy. Different techniques have been proposed in the RE context, including the Analytical Hierarchy Process (AHP) (Al-Yahyai et al., 2012; Cucchiella et al., 2017; Garcia-Cascales et al., 2012; Kahraman and Kaya, 2010; Kahraman et al., 2009), the Technique to Order Preference by Similarity to Ideal Solution (TOPSIS) (Cavallaro, 2010; Gazibey and Çilingir, 2012; Kaya and Kahraman, 2011; Sanchez-Lozano et al., 2016, 2013), Elimination of Choice Expressing Reality (ELECTRE) (Matulaitis et al., 2015; Sanchez-Lozano et al., 2016, 2014), Multi-Objective Optimization by Ratio Analysis plus the full multiplicative form (MULTIMOORA) (Streimikiene et al., 2012), Goal Programming (Khalili-Damghani and Sadi-Nezhad, 2013), VIsekriterijumsko KOmpromisno Rangiranje (VIKOR) (Kaya and Kahraman, 2010) and others (Figueira et al., 2005). Among these MCDM techniques, AHP represents the most widely used and intuitive compared to others, allowing structuring of the problem into different levels and sub-criteria in a hierarchical manner, making it easy for the decision maker to rate the different factors and alternatives (Mangla et al., 2015).

Despite the fact that the SC has been analysed from a sustainability perspective in the RE sector, there are no contributions in the literature that assess the complete PVSC in order to make efficient decisions considering the TBL principles. Therefore, taking into account all the factors involved at each stage of the PVSC, this paper aims to provide a MCDM framework based on AHP and inspired by the TBL principles to assess the suitability of different locations for PV energy production. Moreover, the proposed framework has been tested to assess seven European countries using an extensive literature review and the opinions of three independent experts in the PV sector. The paper makes three main contributions to the literature. The first is the identification of the sub-criteria involved in the decision making process at each stage in the PVSC and the design of the MCDM framework based on the AHP. The second contribution consists of the application of the proposed framework, in combination with expert opinion, to the assessment of seven European countries. Finally, the proposed work reinforces the literature on MCDM applications, providing shareholders with a tool to make more accurate investment decisions when selecting a suitable location for sustainable deployment of PV energy.

The remainder of this paper is structured as follows. Section 2 gives an extensive literature review on MCDM models, TBL principles and SSC in the RE context. Section 3 focuses on the definition of the PVSC framework proposed in this research, with an explanation of the selected dimensions and sub-criteria. Section 4 defines the methodology used. Section 5 presents and discusses the results and, finally, Section 6 summarises the main conclusions and recommendations for investors in PV energy.

2. Literature review

This section reviews the literature on MCDM methods, TBL and SSC. Due to the large number of publications on these topics, the analysis has focused mainly on RE in order to identify the gaps between theory and practice and then develop a framework defining a sustainable supply chain in the PV energy sector based on the TBL approach.

2.1. Decision making frameworks in the renewable energy context

The recent literature on the assessment of RE systems presents the resolution of diverse MCDM problems using different approaches. The analysis of these works leads us to address different issues, such as the suitable site location, the distribution and exchange of produced energy, the autonomous production and self-consumption of energy, the best RE technology alternative or the most appropriate RE policy selection.

Concerning the site location, most of the contributions deal with the selection of the most suitable locations to build RE facilities. The work of Liu et al. (2017) proposes a MCDM model to select the optimal alternative for a PV plant between four cities based on grey cumulative prospect theory for sustainability using AHP methodology. Also, the work of Sanchez-Lozano et al. (2016) identifies previously the suitable locations of PV power plants by Geographical Information System (GIS) and uses AHP to obtain the weights of the different sub-criteria involved in the decisional problem. Afterwards the suitable locations are evaluated and classified by means of the TOPSIS and ELECTRE. Other works of the same authors propose the combination of GIS and ELECTRE-TRI method using the Decision Support System IRIS (Sanchez-Lozano et al., 2014), and the combination of GIS with AHP and TOPSIS to evaluate the optimal sites for solar power plants location (Sanchez-Lozano et al., 2013). Similar works are proposed by Uyan (2013), where the determination of the most suitable site selection for solar farms is resolved using GIS and AHP, or the work of Al-Yahyai et al. (2012) with a study using GIS and Analytic Hierarchy Process with Ordered Weigh Averaging (AHP-OWA) to classify lands in function of some sustainable criteria to make decisions for wind farm installation. On the other hand, Fichera et al. (2018) proposed an optimisation strategy to support urban planners in the decision-making process for urban energy strategies; Volpe et al. (2017) studied the effects of customers with RES resources that directly exchanged the electrical energy with private connections among geographically neighbouring users, based on a mathematical model at the scale of urban territories; and Gonzalez de Durana et al. (2014) investigated the energy distribution problem from the perspective of agent-based modelling.

In relation with the analysis of the best technology alternative, Garcia-Cascales et al. (2012) propose TOPSIS to identify the best photovoltaic cell using quantitative and qualitative factors affecting the manufacturing of photovoltaic cells. Furthermore, the work of Gazibey and Çilingir (2012) implements TOPSIS to assess different PV technologies according to their level of efficiency. Streimikiene et al. (2012) proposes the use of MULTIMOORA and TOPSIS to choose the most sustainable electricity production technology. Energy planning is also addressed by Kaya and Kahraman (2011) to select the best energy technology using TOPSIS taking into account technical, economic, environmental and social criteria, and Cavallaro (2010) proposes and tests the validity and effectiveness of a multi-criteria TOPSIS fuzzy method to compare different heat transfer fluids for a sustainable RE project.

Besides, these same methods have been used to analyse, compare and select RE alternatives and policies. The impact of support policies for domestic PV systems is addressed by Matulaitis et al. (2015) using ELECTRE III to determine the most desirable alternative on a multinational level. A multiple criteria group decision making (FMCGDM) approach is proposed by Khalili-Damghani and Sadi-Nezhad (2013) for sustainable project selection using goal programming and TOPSIS to perform a comprehensive framework including economic, environmental and social effects of a RES investment. The selection of the most appropriate energy policy is addressed by Kahraman and Kaya (2010) using AHP. The same authors address the selection of the best RE alternative and production site by means of an integrated VIKOR-AHP methodology (Kaya and Kahraman, 2010). In another research, Kahraman et al. (2009) propose the use of fuzzy axiomatic design application to select the best RES alternative and comparing with fuzzy AHP.

Moreover, a systematic review of MCDM techniques and approaches in sustainable and RE is addressed by Mardani et al. (2015). Despite the fact that these works contribute with great insights to the literature on MCDM in the RE context, the performed analysis of the literature reveals that little attention has been devoted to the analysis of PV energy sector and in particular to assess the sustainability of the PV supply chain based on the Triple Bottom Line (TBL) approach.

2.2. Triple Bottom Line

Elkington (1997) was the first to introduce the Triple Bottom Line (TBL) concept stressing the differentiation of the three main components of sustainability: economic, social, and environmental, emphasising the importance of the environmental and social effects of a project as well as its economic feasibility. The importance of social and environmental issues linked to the traditional economic dimension —widely considered as the main driving force in most business— has been acknowledged in the last years.

The TBL framework not only focuses on the economical profit, but also emphasises the social and environmental profits (Gao and You, 2017; Govindan et al., 2013; Nikolaou et al., 2013). Therefore, organisations should promote and be involved into activities that enhance the environment and the society (Streimikiene et al., 2012). In the extant literature, several authors have focused on the study of RE topics considering the TBL framework. For instance, Cucchiella and D'Adamo (2013) presented a thorough survey on the topic of SC and RE.

Furthermore, other authors address the analysis of the SC in the RE context from different perspectives: the managerial insights for overcoming the barriers of the RE development (Wee et al., 2012), the identification and measure of the SC's impact on each constituent firm's market valuation applied to the solar energy industry (Davies and Joglekar, 2013), the coordination mechanisms of the PVSC considering consumers, government's subsidies and stakeholders decisions (Chen and Su, 2014) and the problem of the installation of PV plants of different sizes facility rooftops in a green supply chain (Abdallah et al., 2013). Finally, Davies and Joglekar (2010) analyse 42 supply chains from the PV energy sector proposing a procedure to disentangle the SC integration effect on the value of the firm.

2.3. Sustainable Supply Chain

In the recent years, the literature has given a great deal of attention to sustainability issues. Sustainability has been defined as *utilizing resources to* *meet the needs of the present without compromising future generations' ability to meet their own needs* (WCED, U.N., 1987). Initially, sustainability initiatives focused mainly on environmental issues but, as the time passes, the research works are adopting economic and social aspects (Ahi and Searcy, 2013; Mota et al., 2015).

Sustainability and supply chain management (SCM) are two concepts thoroughly studied in the literature in an independent way (Seuring, 2013; Seuring and Müller, 2008) but have been integrated to build the concept of sustainable supply chain management (SSCM) due to they exhibit explicit interactions (Wilding et al., 2012b). In the latest literature, some reviews have been published on SSCM from different approaches but with the aim to analyse these concepts in a combined way (Ahi and Searcy, 2013; Carter and Rogers, 2008; Crum et al., 2011; Sarkis et al., 2011; Seuring, 2013; Seuring and Müller, 2008; Wilding et al., 2012a,c).

The research work of Ahi and Searcy (2013) proposes a new definition of SSCM as *"The creation of coordinated supply chains through the voluntary integration of economic, environmental, and social considerations with key inter-organizational business systems designed to efficiently and effectively manage the material, information, and capital flows associated with the procurement, production, and distribution of products or services in order to meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organization over the short- and long-term."* Additionally, the work of Mota et al. (2015) aims to shed light on the question of *how can sustainability be integrated into supply chains' design and planning decisions.*

It is accepted that the SC is a complex network from suppliers to customers, which involves people, technologies, activities, information and resources. Its design and management has the purpose of obtaining the best global performances under specific operating criteria (Aslam and Amos, 2010; Yuce et al., 2014). In addition, the literature highlights that social, environmental and economic factors must be taken into account in addition to other commonly considered performance criteria (quality, cost, flexibility) (Ageron et al., 2012).

The literature also analyses the SSCM on the emerging RE sectors (Garcia and You, 2015). RE and sustainability issues have reframed SCM and design. Currently, RE companies are to a great extent under legislative, political and social requirements to improve the environmental and social performance of their businesses. Therefore, the design of SC taking into account the TBL is a research topic with high interest in the RE sectors. Some research works have been published aiming at the design of SC for RE, such as bioelectricity (Yue et al., 2014) and biofuels (Akgul et al., 2012; Bowling et al., 2011; Yue and You, 2014; Zamboni et al., 2009), but there is a lack of contributions related to PV energy.

In order to recognize the research gap and define our work, Table 1 summarizes and compares the related studies found in the literature. Despite there are many of them addressing the above mentioned topics, a lack of works assessing the SC in the PV sector considering the TBL approach is observed. This paper attempts to cover this gap for the first time. We also provide a framework to make efficient decisions contributing to the sustainable deployment of the PV energy.

3. Factors affecting sustainable PV supply chain development

PVSC is complex and different from other sectors (Chen and Su, 2014), capturing the attention of both public and private actors (Cucchiella and D'Adamo, 2013). The main differences with other supply chains lie first in the attention and support of the public players in the contribution to reach the 2020 RE quota (European Parliament, 2009, 2012b) and the Kyoto Protocol (United Nations, 1998), but also in the disposal and recovery policies, subsidies and support schemes to the industry, and the role of PV investors and prosumers (producer and consumer) to gain economic opportunities and recover the investments. In this sense, although prosumers install RE plants with the primary objective of satisfying their own energy demands, the energy produced but not consumed is also distributed to closer neighbours (Fichera et al., 2018). These consid-

Table 1: Summary of the main contributions found in the literature.

Source	Topic	Method	Approach		
			PV	TBL	SC
Cucchiella et al. (2017)	Environmental and energetic country comparison	AHP		x	
Zhang and Wang (2017)	Government incentive impact on SC	Stackelberg game	x		x
Liu et al. (2017)	PV power plant site selection in a value SC	Grey cumulative prospect theory	x	(1)	x
Sanchez-Lozano et al. (2016)	PV power plant optimal site	GIS, AHP, TOPSIS, ELECTRE	x		
Matulaitis et al. (2015)	PV development	ELECTRE III,	x		
Mardani et al. (2015)	RE, literature review	MCDM techniques		x	
Garcia and You (2015)	Energy. Optimal SC design	Multi-scale modelling and Life Cycle Analysis		x	x
Sanchez-Lozano et al. (2014)	PV site selection	GIS, ELECTRE-TRI	x		
Chen and Su (2014)	PV supply chain coordination	Mathematical modelling	x		x
Cucchiella and D'Adamo (2013)	RE, literature review	Life cycle analysis, LR		x	x
Davies and Joglekar (2013)	PV supply chain integration	Linear regression	x		x
Abdallah et al. (2013)	PV installation on rooftops	NVP analysis	x		
Khalili-Damghani and Sadi-Nezhad (2013)	Sustainable project selection	FMCGDM		x	
Sanchez-Lozano et al. (2013)	PV power plant site location	GIS, AHP, TOPSIS	x		
Uyan (2013)	PV power plant site location	GIS, AHP	x	(1)	
Yue et al. (2014)	Sustainable biomass-to-electricity SC	MILFP		(1)	x
Al-Yahyai et al. (2012)	Wind farm site selection	AHP-OWA		x	
Garcia-Cascales et al. (2012)	PV cells evaluation	AHP, TOPSIS	x		
Gazibey and Çilingir (2012)	PV technology selection	TOPSIS	x	x	
Wee et al. (2012)	RE supply chains performance	Analysis		x	x
Streimikiene et al. (2012)	Electricity technologies evaluation	MULTIMOORA, TOPSIS	x	x	
Akgul et al. (2012)	Biofuel SC optimisation	MILP			x
Bowling et al. (2011)	Biorefinery facility location and SC optimization	MILP			x
Kaya and Kahraman (2011)	Energy planning evaluation	TOPSIS	x	x	
Cavallaro (2010)	CSP thermal-energy storage	TOPSIS			
Davies and Joglekar (2010)	Market value and SC integration	Linear regression	x		x
Kahraman and Kaya (2010)	Energy policy	AHP	x	x	
Kaya and Kahraman (2010)	RE alternative selection	VIKOR, AHP	x	x	
Kahraman et al. (2009)	RE alternative selection	AD, AHP	x	x	
Zamboni et al. (2009)	Bioethanol SC optimization	MILP			x

(1) Considers environmental and economic factors

erations, linked to the fact that there are a mix of major and minor players along the SC, make the analysis and evaluation of the PVSC a complex and multi-variable problem.

Considering the sustainable SC as a wheel composed of six spokes exemplifying the most relevant functions in the SC (sourcing, transformation, delivery, value proposition, customers, and recycling) (Hassini et al., 2012), we can identify the major factors that have an impact on them. On the other hand, and based on the literature review, we grouped these factors into the three dimensions of sustainability, according to the TBL. As the result, a framework of the PVSC with its main tiers, players, and the selected sub-criteria associated with the SC levels is proposed in Figure 1.

To select our portfolio of the different countries alternatives to investigate, we relied on the top seven countries that have carried out the largest development of the photovoltaic sector in the last fifteen years in Europe: Germany, Italy, UK, France, Spain, Belgium, and Greece.

3.1. Sub-criteria for sustainable PVSC development

This subsection focuses on the sub-criteria selection affecting sustainable supply chain development for PV energy production. Table 2 shows the sub-criteria associated with social, economic and environmental dimensions that have been selected to evaluate the PV sustainable supply chain, with their corresponding data sources and measure units.

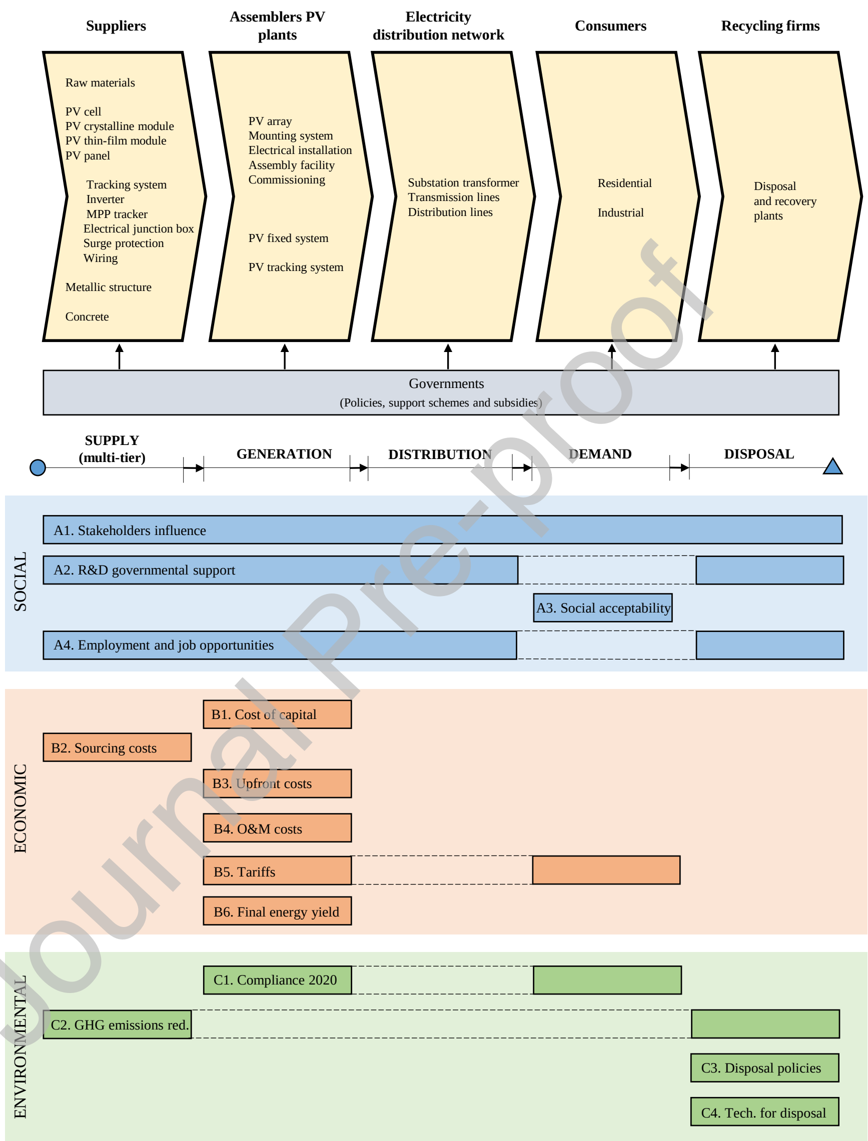

Figure 1: Photovoltaic Supply Chain

Table 2: PV sustainable supply chain sub-criteria in country selection.

	Sub-criteria	Unit	Description	Data source
A. SOCIAL	A1.Stakeholders influence	Logical	Relationship with suppliers, customers, local communities and NGOs.	Ahi and Searcy (2013); Carter and Rogers (2008); Fichera et al. (2018); Gonzalez de Durana et al. (2014); Govindan et al. (2013); Volpe et al. (2017); and Experts' survey
	A2.R&D governmental support	M€	Total expense on solar energy research per year	Dusonchet and Telaretti (2015); IEA (2015b); Mota et al. (2015)
	A3.Social acceptability	%	Concerns the ability for regulators, policymakers and other key stakeholders to craft effective policies or frameworks that create and foster community and market acceptance. It includes the socio-political acceptance, market acceptance and community acceptance	IEA (2015b, 2016); Sovacool and Lakshmi Ratan (2012); Troldborg et al. (2014)
	A4.Employment and job opp.	Person-year	Average amount of labour places in the PV sector per year	IEA (2015b,c, 2016); You et al. (2012)

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	Sub-criteria	Unit	Description	Data source
B. ECONOMIC	B1.Cost of capital	%	Rate of return a investor/country expects to obtain considering the best investment alternative with equivalent risk	DIA-CORE Project (2016)
	B2.Sourcing costs	€/W_p	The costs of raw materials and commodities purchased in the country and from foreign countries to build the PV plants	Ageron et al. (2012); Freeman and Chen (2015); IRENA (2012); Lima-Junior and Carpinetti (2016); Liou et al. (2014); Wirth (2016); Zhang et al. (2014)
	B3.Upfront cost	€/W_p	Total investment of the PV power plant project	Bazilian et al. (2013); IEA (2015b); Ramírez et al. (2017)
	B4.O&M costs	€/kW_{year}	Operation and maintenance costs including general site management costs, electrical inspection costs, panel washing and vegetation control costs, inverter maintenance costs and insurance costs	Campoccia et al. (2014); Dusonchet and Telaretti (2015); Honrubia-Escribano et al. (2018); Keating et al. (2015); Ramírez et al. (2017)
	B5.Tariffs and incentives	€/kWh	Total payments per kWh of generated electricity received by the producer with a fixed price	Dusonchet and Telaretti (2015); Honrubia-Escribano et al. (2018); IEA (2015b, 2016); Pyrgou et al. (2016); Ramírez et al. (2017)

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	Sub-criteria	Unit	Description	Data source
	B6.Final energy yield	kWh/kW_p	Average solar irradiation in the country location	European Commission (2016)
C. ENVIRONMENTAL	C1.Compliance with 2020 PV share	%	Promotion of the use of energy from renewable sources set an overall goal across the EU for a 20% share of energy consumption to be derived from renewable sources by 2020.	Directive 2009/28/EC of the European Commission (Dehler et al., 2015; Eurostat, 2017; Fichera et al., 2018; Gonzalez de Durana et al., 2014; Volpe et al., 2017)
	C2.GHG emissions reduction	%	Reduction of the primary greenhouse gas emitted due to the use of photovoltaic energy instead of the combustion of fossil fuels for energy.	Dehler et al. (2015); Hosenuzzaman et al. (2015); Kucukvar et al. (2014); Troldborg et al. (2014)
	C3.Disposal green policies	Logical	Measures to protect the environment and human health	Bilimoria and Defrenne (2013); European Parliament (2012a); Goe and Gaustad (2014); Paiano (2015); Tao and Yu (2015) and Experts' survey
	C4.Technology for disposal	Logical	Technologies and recycling ways including manufacturing waste recycling, end-of-life or used module material recycling, re-manufacturing and reuse	Tao and Yu (2015) and Experts' survey

3.1.1. Social sub-criteria

The social dimension of sustainability *concerns the impacts the organisation has on the social system within which it operates* (GRI, 2013). Social sub-criteria include the impacts on the public perception, employment creation and governmental support. The main social indicators selected for sustainable PV supply chain development in this research are stakeholders influence, R&D governmental support, social acceptability and employment and job opportunities.

- Stakeholders influence (A1) measures the relationship with suppliers, customers, local communities and non-governmental organisations (NGOs) inside the SC. Several authors have adopted this criterion in the assessment of the social dimension of sustainable SCM considering specific references to stakeholders, and including (but not limited to) governments, customers, consumers and suppliers (Ahi and Searcy, 2013; Carter and Rogers, 2008; Govindan et al., 2013; Seuring, 2013). The criterion is measured in qualitative terms by means of linguistic labels using the experts opinion and make up a criterion to maximise.

- R&D governmental support (A2) assesses the impact of economic incentives that contribute to technology growth, job creation and regional development. These subsidies are focused on the development of new PV installations aiming to improve and promote the solar energy and stimulate the market (Avril et al., 2012). Authors agree that this criterion should be considered when deciding on facility location (Mota et al., 2015; Sovacool and Lakshmi Ratan, 2012) and that in order to have a successful PV project there must be a link between the financial support and the location where the PV system is installed (Dusonchet and Telaretti, 2015). In this research, this criterion is valued in million of euro, measuring the total R&D support per year in each country and constitute an indicator to be maximised.

- Social acceptability (A3) is a significant criterion in the assessment of the PVSC since public opposition and reluctance to the development of the

PV sector is currently a barrier in some countries, such as UK and others (Troldborg et al., 2014; West et al., 2010). The literature recognises the assessment of the social acceptability of PV energy in not simple and "has multiple dimensions –socio-political, community, and market– that must be met holistically in order for investors and users to embrace renewable energy" (Sovacool and Lakshmi Ratan, 2012). Some studies are based on surveys that in general exhibit high levels of acceptability at country level but, in contrast, show disagreement at local level (Troldborg et al., 2014). The assessment of social acceptability is measured here as PV market penetration due to the relationship between the acceptability and the rapid acceleration of solar panels in countries like Germany (Sovacool and Lakshmi Ratan, 2012). It is a criterion to be maximised.

- Employment and job opportunities (A4) is a key factor in the social pillar of the TBL approach. Different authors have used this indicator to measure how sustainability is integrated into the SC design and planning decisions referred to objective and quantifiable metrics (Hutchins and Sutherland, 2008; You et al., 2012). In this research, this is a quantitative indicator assessed with the data from the International Energy Agency (IEA) (IEA, 2015a,b, 2016) measuring the average amount of labour places in the PV sector per year in each selected country. This is a criterion to be maximised.

3.1.2. Economic sub-criteria

The economic dimension of the TBL approach is a key issue as economic profitability of the RE projects and the main driver for the energy technologies penetration in the markets (Streimikiene et al., 2012). In the literature, economic dimension is mainly evaluated using the indicators that most directly impact on the profitability of the project investments: cost of capital, sourcing and upfront costs, operation and maintenance cost, governmental subsidies and final energy yield (Barboza, 2015; Gao and You, 2017; Govindan et al., 2013; Ramírez et al., 2017).

- Cost of capital (B1) is the minimum rate of return that an investor expects to obtain considering the best investment alternative with equivalent risk. Generally, it is measured by means of the weighted average cost of capital. In our work, this quantitative indicator has been selected by country (DIACORE Project, 2016) and constitute a criterion to minimize. The values are detailed in Table 3.

- Sourcing costs (B2) refers to the costs of raw materials and commodities purchased in the country or in foreign countries. These are significant costs in the PV installations because the cost of panels and inverters constitute more than half of the total plant cost in most countries (IRENA, 2012; Ossenbrink et al., 2013; Ventre et al., 2001; Wirth, 2016; Wiser et al., 2009). During the last years, the research and development efforts made in the field of materials science have motivated the materials cost reduction for solar cells manufacturing, improving the total upfront costs and allowing for the adoption of PV energy (Ramírez et al., 2017). In the SC assessment the sourcing costs are directly related to the supplier selection (Ageron et al., 2012; Freeman and Chen, 2015; Lima-Junior and Carpinetti, 2016; Liou et al., 2014; Zhang et al., 2014). In this research, sourcing costs is an indicator to minimise and the values, in €/W_p, have been obtained from the literature (IEA, 2015b, 2016; IRENA, 2012; Ossenbrink et al., 2013; Wirth, 2016) for the selected countries, Table 3.

- Upfront costs (B3) are measuring the total expenses charged at the onset of a PV power plant project. The non-sourcing costs (mounting hardware, installation labour, fees, shipping, overhead, taxes) have a different value depending on the country as well (IEA, 2015b). In this line, Table 3 presents the PV upfront costs considered in the present work, in €/W_p, which are based on the review conducted recently by the authors in (Ramírez et al., 2017). Actually, this price-per-watt (peak) metric has the virtue of simplicity and availability of data (Bazilian et al., 2013). It constitutes an indicator to be minimised.

- Operation and maintenance (O&M) costs (B4) include a wide variety of expenses in the operation of a PV plant, as general site management costs, electrical maintenance costs, panel washing costs, vegetation control costs, insurance costs and others. These are not significant costs due to the distinctive feature of the PV plants having high upfront costs but low operation costs (Jäger-Waldau et al., 2011; Ramírez et al., 2017), in contrast to other conventional energy sources. In this research, this is a criterion to be minimised. The data of the O&M costs have been obtained from the literature for the selected countries (Campoccia et al., 2014; Dusonchet and Telaretti, 2015; Enbar and Weng, 2015; Keating et al., 2015). The values are detailed in Table 3.

- Tariffs and incentives (B5) have been adopted in the last decade to stimulate the development of long-term PV projects in the most of European countries. Feed-in tariffs are, by far, the most extensively support scheme adopted all over the world (Dusonchet and Telaretti, 2015). Under this scheme, the utilities are mandatory to purchase the produced PV energy at a fixed-tariff price. In addition, this payment must be guaranteed for a fixed period, typically between 20 and 25 years. Due to the dependence of this support scheme on PV energy adoption, it is mandatory to consider this in the economic assessment of the PVSC. So, this research includes it measuring the total payment in €/kWh in the selected countries. The values have been obtained from the literature (Dusonchet and Telaretti, 2015; IEA, 2015b, 2016; Pyrgou et al., 2016; Ramírez et al., 2017). This indicator needs to be maximised.

- Final energy yield (B6) is a key factor for the economic evaluation of a PV plant because it determines the production of PV energy. This factor depends on the solar irradiation level and, in turn, the plant location. Solar irradiation data are widely used in the estimation of PV energy production. Several radiation databases are available. This research uses the information provided by the Photovoltaic Geographical Information System (PVGIS) (European Commission, 2016). It is a criterion to maximise in this research. The values are measured in kWh/kW_p and presented in Table 3.

3.1.3. Environmental sub-criteria

This subsection analyses the main environmental dimension indicators for the PVSC development. Literature on sustainable SC is comprehensive and diverse and there are a plenty of works studying and evaluating its environmental impacts (Mota et al., 2015; Zhang et al., 2014). Beyond the available methods, it is accepted that environmental impact analysis must take into account the entire life of the SC, from the extraction of resources, through production, use, disposal and recycling (European Commission, 2012). From the literature review, four sub-criteria are selected in this research to assess the environmental impact of the PVSC, as follows:

- Compliance of 2020 RES target share (C1) is based on the directive 2009/28/EC (European Parliament, 2009) of the European Commission setting an overall goal across the EU for a 20% share of energy consumption to be derived from RES by 2020. All the EU members have their own national target 2020 for all the RES (European Commission, 2010a). The PV national target 2020 and the evolution of the PV power installed in the selected countries is available in Eurostat (2017) and Dehler et al. (2015). It constitutes a criterion to be maximised, whose values are presented in Table 3.

- Reduction of GHG emissions (C2) is one of the most common used criterion in the evaluation of RE and sustainability (Kucukvar et al., 2014; Troldborg et al., 2014). Most of studies assess the reduction of GHG emissions comparing the use of RE technologies with the non-RE ones that are replacing. PV energy is a zero emissions energy system (European Commission, 1998; Owusu and Asumadu-Sarkodie, 2016). During the operation of the PV plants there are zero emissions of CO_2, NO_x and

SO_2 gases (Hosenuzzaman et al., 2015). In addition, PV energy does not contribute to global warming. Table 3 includes the GHG emissions reduction rates in the selected countries. These values have been calculated based on the reduction of CO_2 emissions on the energy mix related to each country. It is a criterion to be minimised.

- Disposal green policies (C3) refers to the measures aiming at protecting the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste from electrical and electronic equipment and by reducing the overall impacts of resource use and improving the efficiency of such use. In the PV energy context, the treatment and disposal of the PV waste has emerged as a concern in the EU members (Bilimoria and Defrenne, 2013). The huge quantity on PV panels that will need to be disposed by 2025 forced the European Union to address this environmental impact by the Directive 2012/19/EU (European Parliament, 2012a). For this aim, the PV panels must be appropriately collected and treated to more effectively control the disposal and promote the recovery and recycling of materials. Some authors have contributed on this issue: the study of the potential opportunity for energy savings from recycling PV (Goe and Gaustad, 2014), the analysis of the waste flows to enhance the appropriate disposal of the hazardous materials as well as the importance of the recovery and recycling of these resources (Paiano, 2015), or the review of feasible recycling technologies and ways of PV modules as well as the potential environmental benefits and economic viability of PV module recycling (Tao and Yu, 2015). In this research, this is a criterion to be maximised and has been evaluated for the selected countries by the experts' opinion, and using a qualitative scale.

- Technology for disposal (C4) concerns the technologies and recycling ways including manufacturing waste recycling, end-of-life or used module material recycling, re-manufacturing and reuse. The current recycling tech-

Table 3: Values of the sub-criteria for sustainability assessment of the PVSC in the selected countries

Sub-criteria		Unit	Country						
			Germany	Italy	UK	France	Spain	Belgium	Greece
Social	A1	Logical	L	L	L	L	L	L	L
	A2	$M€/year$	49.76	7.28	11.19	8.46	21.74	3.82	1.08
	A3	%	7.10	8.00	2.60	1.50	3.40	4.10	7.40
	A4	$Lplaces/year$	60000	12000	16900	9400	7500	3000	2000
Economic	B1	%	4.5	9.0	6.5	5.7	8.0	6.0	12.0
	B2	$€/W_p$	0.59	0.53	0.58	0.60	0.55	0.65	0.50
	B3	$€/W_p$	1.00	1.03	1.16	1.30	1.20	1.30	1.00
	B4	$€/kW_{year}$	37.00	38.11	42.92	48.10	44.40	48.10	37.00
	B5	$€/kWh$	0.119	0.052	0.129	0.186	0.059	0.049	0.110
	B6	kWh/kW_p	1122	1481	1081	1317	1895	1128	1729
Environ-mental	C1	%	76.6	100.5	46.6	62.2	81.0	61.5	85.0
	C2	%	13.78	11.96	5.82	35.40	11.94	16.94	12.53
	C3	Logical	L	L	L	L	L	L	L
	C4	Logical	L	L	L	L	L	L	L

nologies for PV materials and end-of-life modules have been thoroughly explored and most of them are commercially available. Nowadays, new challenges lie in increasing the process efficiency and reducing the process complexity, energy requirements, and the use of chemicals. This is a criterion to be maximised and has been assessed by means of the experts' opinion.

4. Research methodology

This section details the methodology used, starting from the MCDM framework based on AHP to the data collection.

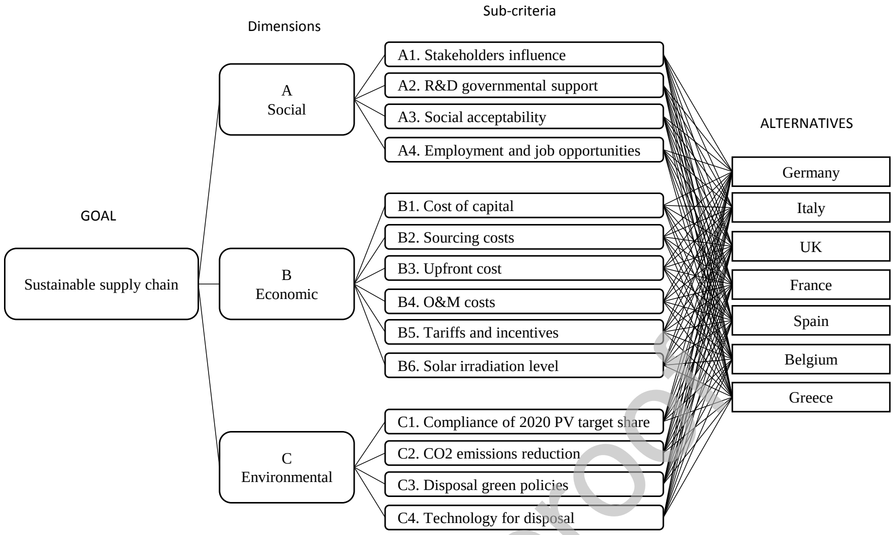

Figure 2: AHP framework for sustainable supply chain.

4.1. AHP technique

AHP (Saaty, 1980), is one of the most widely used MCDM techniques because it is easy to implement (Luthra et al., 2016). It has recently been employed to solve several complex decision making problems. Balfaqih et al. (2017) have employed AHP to assess the environmental and economic performance of desalination supply chain, Zimmer et al. (2017) to assess social risks of global supply chains and supplier selection in Germany, Dweiri et al. (2016) proposed an AHP decision support model for supplier selection in automotive industry in Pakistan, de Oliveira Moura Santos et al. (2017) used AHP for suppliers segmentation, Asgari et al. (2015) for sustainability ranking of UK major ports.

AHP consists of structuring the decisional problem into different hierarchical levels such as a main goal, main dimensions, sub-criteria and alternatives, followed by a pairwise comparison at each level. Figure 2 represents the AHP structure for our sustainable supply chain decision making problem.

Once the framework has been defined, experts compare each main dimension against the others using a nine-point Saaty's scale shown in Table 4.

Table 4: Saaty's scale (adapted from (Saaty, 1980)).

Scores	Equivalent linguistic judgment
1	Equally important
3-1/3	Moderately more/less important
5-1/5	Fairly more/less important
7-1/7	Strongly more/less important
9-1/9	Extremely more/less important
2-1/2,4-1/4,6-1/6,8-1/8	Intermediate values

The same procedure is repeated for the sub-criteria which are this time compared with respect to the corresponding main dimension. Finally, the different alternatives are compared with respect to each sub-criterion.

Next step consists of calculating the eigenvalues and eigenvectors of the pairwise comparison matrices in order to determine the weights and rank the different sub-criteria and alternatives. As an illustrative example, consider the following matrix M:

$$M = \begin{bmatrix} 1 & 3 & 9 \\ 1/3 & 1 & 5 \\ 1/9 & 1/5 & 1 \end{bmatrix}$$

According to (Saaty, 2008), the steps to calculate the exact priorities consist of raising the matrix to a large power, summing up the matrix along the rows and finally dividing each by the sum of all the rows in order to normalise the weights. The priorities of M are $[0.672, 0.265, 0.063]^T$.

Finally, a consistency ratio (CR) needs to be computed for each matrix in order to assess the consistency of the experts' judgement. CR is given by CI/RI, with $CI = (\lambda_{max} - n)/(n-1)$, where λ_{max} is the maximum Eigen value and n is the size of the matrix. RI represents a random index depending on n and it can be found in table 5. The value of CR must be lower than 0.10 for an acceptable level of consistency.

Table 5: Random Index (adapted from (Saaty, 1980)).

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

In our example, CR associated to matrix M is equal to 0.0251, which means the judgement is consistent.

The overall weights for the alternatives are obtained by multiplying their priorities by its sub-criteria's and dimensions' priorities and finally summing up the resulting values for each alternative.

4.2. Data collection

In order to test and validate our framework, three independent experts in the photovoltaic sector were approached, in line with (Garcia-Cascales et al., 2012). The Expert 1 is a technical manager with 16 years of experience in photovoltaic and wind energy. He works for a multinational company of RE with operations in the entire world. The company employs 3,700 people and has facilities in 22 countries. Expert 2 is a highly regarded academic and senior researcher in RE with 25 years of experience. He works in a university and manages a RE research center. Expert 3 is an expert on photovoltaic energy. She is a technical manager of a multinational company with operations in Spain, USA, India, Mexico, Chile and South Africa, employing 550 people. At the initial stage of this research, after the literature review, experts' opinions were used to refine our model and consider the factors more relevant to the PV supply chain.

AHP is often combined with Delphi method for participatory decision-making processes for consensus building, as proposed by (Le Pira et al., 2017). In this paper, a Pseudo-Delphi technique was used to collect the knowledge from the experts as per (Garcia-Cascales et al., 2012) since they did not interact at any time neither in the data collection nor in the decision-making process. A questionnaire was sent to the three experts with the different alternatives to select

Table 6: Expert 1 pairwise comparison matrices of sub-criteria with respect to main dimensions.

A	**A1**	**A2**	**A3**	**A4**
A1	1	7	1/2	1/3
A2	1/7	1	1/8	1/9
A3	2	8	1	1/2
A4	3	9	2	1

(a) Social dimension

B	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**
B1	1	2	1/3	3	1/2	1/4
B2	1/2	1	1/4	2	1/3	1/5
B3	3	4	1	5	2	1/2
B4	1/3	1/2	1/5	1	1/4	1/6
B5	2	3	1/2	4	1	1/3
B6	4	5	2	6	3	1

(b) Economic dimension

C	**C1**	**C2**	**C3**	**C4**
C1	1	1/3	1/2	5
C2	3	1	1/2	6
C3	2	2	1	7
C4	1/5	1/6	1/7	1

(c) Environmental dimension

the most appropriate answer for each question. In addition to the questionnaire, an explanation of the multi-criteria decision-making problem, main dimensions and related sub-criteria, diagrams of the PVSC and the hierarchical structure were added so that the three experts had the same information. This process demanded two months to complete the questionnaires. The questionnaire was designed in two parts:

1. The first part of the survey lied in rating the sub-criteria for each dimension, by filling in three matrices, as shown in Table 6 for Expert 1.
2. The second one was focused on the assessment of the alternatives countries for the qualitative sub-criteria A1, C3 and C4. The experts were asked to rate the seven European countries under study with respect to each sub-criterion. As an example, Table 7 shows the Expert 1 pairwise comparison

Table 7: Expert 1 pairwise comparison matrix of alternatives with respect to A1 sub-criterion.

A1	Germany	Italy	UK	France	Spain	Belgium	Greece
Germany	1	8	5	8	7	9	9
Italy	1/8	1	1/4	1	1/2	2	2
UK	1/5	4	1	4	3	5	5
France	1/8	1	1/4	1	1/2	2	2
Spain	1/7	2	1/3	2	1	3	3
Belgium	1/9	1/2	1/5	1/2	1/3	1	1
Greece	1/9	1/2	1/5	1/2	1/3	1	1

matrix of alternatives with respect to A1 sub-criterion.

Concerning the quantitative sub-criteria, the assessment of the alternatives was made with the data from the peer-reviewed literature and summarised in Table 3. Each country was compared against each other using a nine point Saaty's scale shown in Table 4, and for each of the quantitative sub-criteria A2, A3, A4, B1, B2, B3, B4, B5, B6, C1 and C2. With regard to A2 sub-criteria, R&D governmental support, and based on the literature review, Germany carried out the highest effort in the total expense on solar energy research in 2014, with 49.76 Million of €, in front of Greece with a yearly expense of 1 Million of €. Therefore, we scored Germany as 9 over 1 with respect to Greece. The same procedure was performed with the other countries having into account the yearly expenses in R&D in each country by 2014: Spain (21.74 M€), UK (11.19 M€), France (8.46 M€), Italy (7.28 M€) and Belgium (3.82 M€). We have incorporated these arguments in Table 8.

In terms of the other quantitative sub-criteria, the same procedure and analysis based on the peer-reviewed literature was applied, obtaining the corresponding pairwise comparison matrices. Once all the matrices were filled, weights, Eigen values and Consistency Ratio were calculated.

Finally, four scenarios were analysed, each giving a different importance to

Table 8: Pairwise comparison matrix of alternatives with respect to A2 sub-criterion.

A2	Germany	Italy	UK	France	Spain	Belgium	Greece
Germany	1	8	7	8	6	9	9
Italy	1/8	1	1/2	1	1/3	2	2
UK	1/7	2	1	2	1/3	2	3
France	1/8	1	1/2	1	1/3	2	2
Spain	1/6	3	3	3	1	4	4
Belgium	1/9	1/2	1/2	1/2	1/4	1	2
Greece	1/9	1/2	1/3	1/2	1/4	1/2	1

Table 9: Definition of weights for each dimension depending on the scenario.

	Social dimension	Economic dimension	Env. dimension
Scenario 1	0.33	0.33	0.33
Scenario 2	0.50	0.25	0.25
Scenario 3	0.25	0.50	0.25
Scenario 4	0.25	0.25	0.50

the three dimensions, economic, social and environmental, in order to cover the main range of priorities for the dimension, Table 9. In the first scenario, the three dimensions had the same importance; in the second scenario, double importance was given to social dimension compared to environmental and economic; in the third scenario economic dimension was the most important, while in the fourth scenario environmental dimension was the priority.

Finally, in order to combine the judgements of the three experts and the assessment of the quantitative sub-criteria, the geometric mean of the final priorities for the alternatives was calculated according to (Saaty, 2008) as follows.

$$\sqrt[n]{\prod_{i=1}^{n} P_i}$$

With n number of experts and P_i final priority for the alternatives of each expert.

As a matter of fact, a consensus vote is used when the experts are able to agree on the values of the matrices or on the priority vectors; vice versa, mathematical aggregation is adopted (Ignaccolo et al., 2017). Moreover, the experts may not wish to combine their judgements but only their final outcomes obtained by each from their own hierarchy (Saaty, 2008).

Under this framework, Figure 3 shows the sequence of steps of the adopted methodology for sustainable supply chain development.

5. Results and discussion

Based on the methodology defined in Section 4, a total of twenty-nine matrices were obtained: nine for sub-criteria comparisons (three for each expert), nine for comparison of alternatives with respect to logical (or qualitative) sub-criteria (three for each expert), eleven for the comparison of the alternatives with respect to quantitative sub-criteria. The maximum CR value estimated among the twenty-nine filled matrices is 0.099, which means the experts' judgments have an acceptable level of consistency.

Table 10 shows the priorities of the sub-criteria with respect to the corresponding main dimension. Sub-criterion A4 "Employment and job opportunities" was recognised as the most relevant for the social dimension by Experts 1 and 2, while Expert 3 prioritised A1 "Stakeholders influence" and A4 was evaluated with the lowest weight. Regarding the economic dimension, Experts 1 and 2 give the same result again, providing the highest weight to B6 "Final energy yield", while for Expert 3 this B6 would be in the second position, giving the highest priority to B1 "Cost of capital". Finally, under the environmental

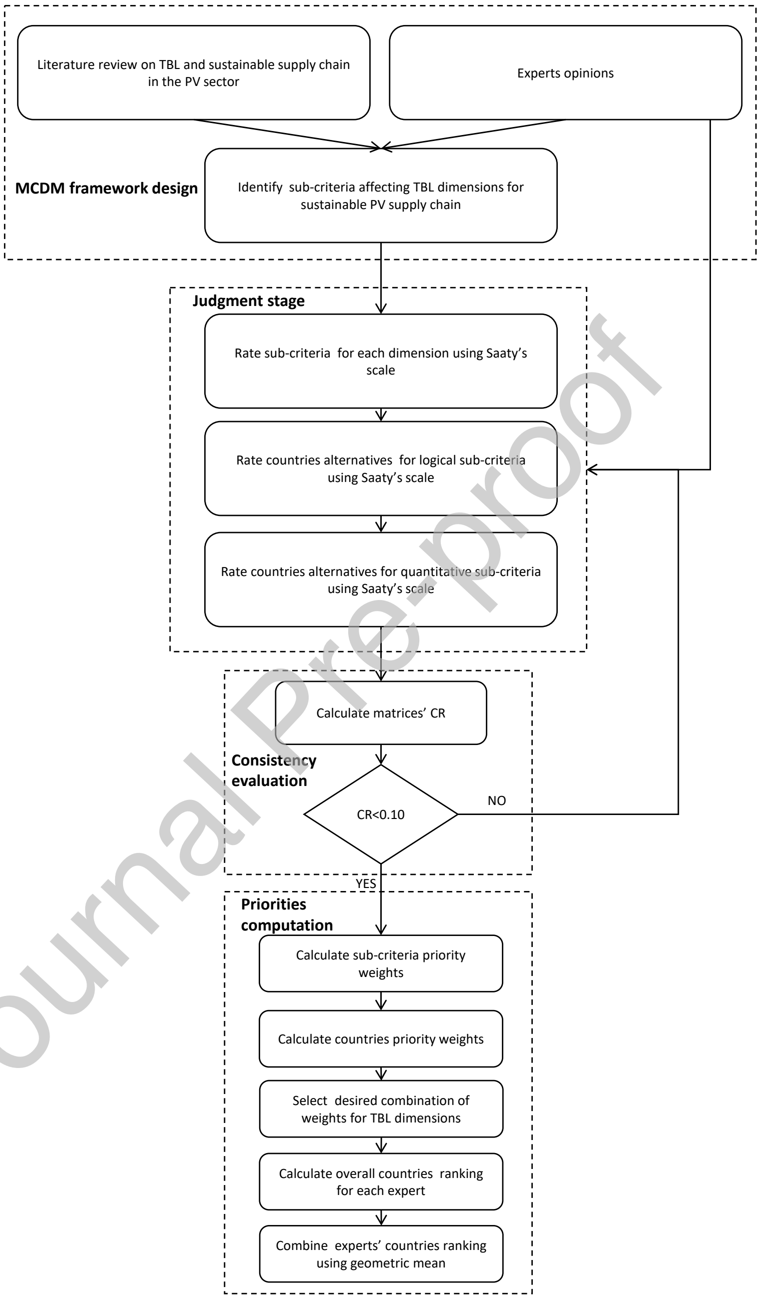

Figure 3: Proposed sustainable supply chain evaluation methodology

Table 10: Priorities of sub-criteria from Experts opinion.

Sub-criteria	Priorities		
	Expert 1	**Expert 2**	**Expert 3**
A1	0.185	0.159	**0.522**
A2	0.038	0.039	0.200
A3	0.296	0.248	0.200
A4	**0.481**	**0.553**	0.078
B1	0.101	0.206	**0.268**
B2	0.064	0.052	0.206
B3	0.250	0.056	0.077
B4	0.043	0.026	0.029
B5	0.160	0.228	0.199
B6	**0.383**	**0.432**	0.222
C1	0.182	0.131	0.066
C2	0.334	0.161	0.103
C3	**0.435**	**0.354**	0.324
C4	0.049	**0.354**	**0.508**

dimension, Expert 1 prioritised C3 "Disposal green policies", Expert 3 considered C4 "Technology for disposal" as the most relevant sub-criterion, while Expert 2 rated equally C3 and C4.

Priorities of the alternative countries with respect to the sub-criteria, both qualitative and quantitative, are given in Tables 11 and 12, respectively. With regard to the qualitative sub-criteria, Table 11, experts have provided a similar assessment. Germany has obtained the highest priority for Experts 1 and 3 with regard to sub-criterion A1 "Stakeholders influence". The three experts prioritise Germany with respect to sub-criterion C3 "Disposal green policies". Experts 1 and 2 prioritise Germany with respect to sub-criterion C4 "Technology for disposal" as well. A similar result is obtained from the quantitative sub-criteria evaluation, Table 12, where Germany has obtained the highest priority for sub-criteria A2, A4, B1, B3, B4. Italy presents the highest priority for sub-criterion A3 due to its largest PV market penetration. Greece holds the highest priority for sub-criteria B2, B3 and B4 due to the reduced sourcing, upfront and O&M costs experienced by this country. France poses a remarkable largest priority for sub-criterion B5 due to the high French FiT value, while Spain presents the largest priority for sub-criterion B6 due to the extraordinary final energy yield found in this Mediterranean country.

By analysing the priorities of the sub-criteria with respect to the main dimensions (Table 10) and the priorities of the alternatives with respect to the sub-criteria (Tables 11 and 12) it is possible to identify possible areas of improvement for each of the considered countries in terms of sustainability of their PV supply chain. As a matter of fact, it is suggested to spend more effort first on increasing the scores for the highest ranked sub-criteria rather than the lowest ones, in order to improve the overall sustainability of the PV supply chain. Thus, Germany should focus first on improving the score on B6, Italy on A4, B1, B5, C4, UK on A3, B6, France on A1, A3, A4, B6, Spain on A3, A4, B1, B5, C3, Belgium on A1, A3, A4, B5, B6, and finally Greece on A1, A4, B1, C3, C4. Each country should adopt appropriate measures to improve their scores on the identified sub-criteria, which may represent a future research opportunity.

In addition, Figure 4 shows the overall ranking for the alternative countries for each considered scenario. It is observed that country 1 (Germany) represents the highest rated alternative and country 3 (UK) and 6 (Belgium) the lowest ones in all scenarios. Scenarios 1 and 2 show almost the same ranking for the alternatives. However, when double importance is given to the economic dimension (Scenario 3), country 7 (Greece) becomes the third and country 2 (Italy) the fifth option. With regard to scenario 4, which represents the highest weight to the environmental dimension, country 4 (France) becomes the second most suitable alternative, followed by countries 2, 5 and 7.

Table 11: Priorities of alternatives with respect to qualitative sub-criteria from Experts opinion.

Sub-criteria	Alternatives	Priorities		
		Expert 1	Expert 2	Expert 3
A1	**Germany**	**0.520**	0.117	**0.302**
	Italy	0.059	**0.356**	0.157
	UK	0.196	0.053	0.147
	France	0.059	0.053	0.082
	Spain	0.095	**0.356**	0.158
	Belgium	0.036	0.033	0.104
	Greece	0.036	0.033	0.050
C3	**Germany**	**0.461**	**0.507**	**0.273**
	Italy	0.097	0.058	0.161
	UK	0.149	0.161	0.064
	France	0.074	0.101	0.157
	Spain	0.156	0.055	0.047
	Belgium	0.037	0.098	**0.273**
	Greece	0.026	0.021	0.026
C4	**Germany**	**0.464**	**0.484**	0.187
	Italy	0.060	0.079	0.086
	UK	0.133	0.175	0.080
	France	0.089	0.068	0.124
	Spain	0.196	0.093	0.232
	Belgium	0.029	0.080	**0.245**
	Greece	0.029	0.021	0.047

Table 12: Priorities of alternatives with respect to quantitative sub-criteria.

Alternatives	A2	A3	A4	B1	B2	B3	B4	B5	B6	C1	C2
Germany	**0.536**	0.237	**0.562**	**0.346**	0.064	**0.298**	**0.299**	0.144	0.032	0.108	0.098
Italy	0.062	**0.350**	0.084	0.047	0.224	0.221	0.219	0.033	0.128	**0.422**	0.093
UK	0.092	0.033	0.128	0.136	0.083	0.080	0.080	0.188	0.029	0.025	0.031
France	0.062	0.024	0.074	0.198	0.049	0.023	0.023	**0.458**	0.071	0.049	**0.519**
Spain	0.168	0.048	0.068	0.070	0.154	0.057	0.057	0.039	**0.440**	0.153	0.069
Belgium	0.045	0.071	0.042	0.181	0.023	0.023	0.024	0.029	0.036	0.049	0.116
Greece	0.035	0.237	0.042	0.021	**0.404**	**0.298**	**0.299**	0.109	0.265	0.196	0.076

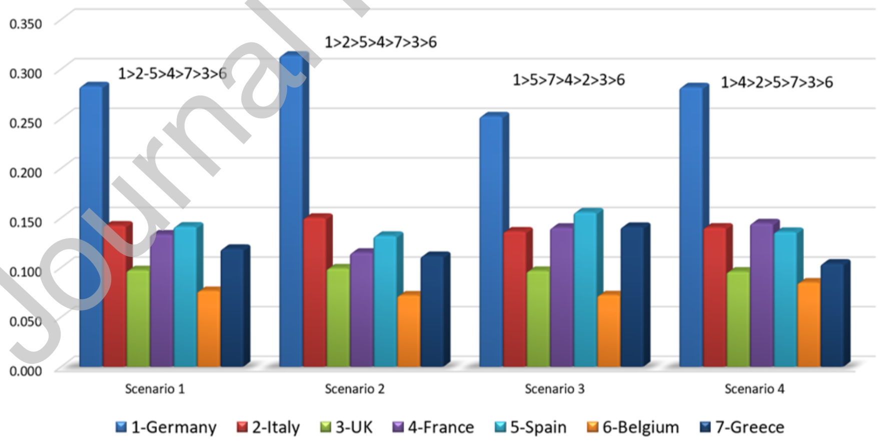

Figure 4: Overall ranking of alternatives for each considered scenario.

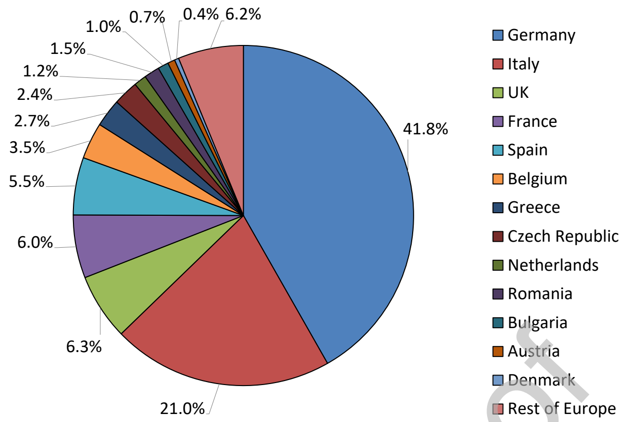

Figure 5: European solar PV cumulative installed capacity 2000–2017 (in percentage by country).

5.1. Justification of results

The results obtained in terms of ranking of the considered countries were compared against data concerning the PV sector evolution in all European countries in the period 2000-2016. Figure 5 shows the cumulative percentage installed PV capacity in the European countries in the mentioned period (IEA, 2016; REN21, 2016; SPE, 2017). It can be seen that Germany, Italy and France are the countries with the higher photovoltaic development, followed by UK, Spain, Belgium and Greece.

Analysing and comparing the results obtained in figure 4 with figure 5, it is observed that the results are in good agreement, with Germany and Italy in the top position in both analysis and Greece and Belgium in the lower places. However, it is shown that UK came sixth in the ranking of the countries according to the applied methodology (figure 5), while it occupies the third place for PV development (figure 4). This difference could be explained from the yearly analysis of the PV sector evolution in this country during the period 2000-2014. Specifically, the development of the PV sector in UK began in 2011 and it was not until 2013 (1.07 GW) and 2014 (2.41 GW) when occurred the main increasing in the PV installed capacity. A more detailed explanation of the PV evolution in the European countries are analysed in the works of (Campoccia et al., 2014), (Dusonchet and Telaretti, 2015) and (Ramírez et al., 2017).

Furthermore, we have presented the resulting rankings to the experts and asked them the following questions:

- Q1: Could you please explain why you prioritised some sub-criteria instead of others?
  - Expert 1: Regarding the social and environmental dimensions, he is in agreement with the highest ranked sub-criteria. However, regarding the economic dimension, he would consider all the sub-criteria being closer in terms of priorities. Moreover, he considers social dimension as the most important dimension and A4 "Employment and job opportunities" as the main sub-criterion because it enables social development and better life conditions. Regarding the economic dimension, he believes that B6 "Solar irradiation level" is the most important sub-criterion as it allows the energy production to be efficient and profitable. The remaining sub-criteria are important, however they depend on the level of maturity of the technology and policies, and thus they are subject to changes, while solar level irradiation is fixed according to the PV power plant location. Finally, he considers C3 "Disposal green policies" as most relevant factor because it is necessary to promote the development and growth of such technologies to increase sustainability.
  - Expert 2: A4 "Employement and job opportunities" is judged as the most important sub-criterion for social dimension because of the jobs created during the construction and running phases of the PV plants, specially in the countries where the unemployement is high, such as Greece and Spain. Regarding the economic dimension, B6 "Solar irradiation level" is the starting point for setting up a PV plant and as such it is the most important sub-criterion. Finally, C3 "Disposal

green policies" and C4 "Technology" are significant sub-criteria for the expert due to the relation that these criteria have with the end-of-life of a PV plant (e.g. the disposal of PV modules is currently a great concern for the governments).

  - Expert 3: According to Expert 3, A1 "Stakeholders influence" is crucial for the social dimension, because of the cost of the technology and the absence of subsidies and regulated tariffs. Also, A3 "Social acceptability" is a significant sub-criterion for the expert due to the acceptance on the use and promotion of PV energy moves the investment decisions that drive in turn the development of this sector. Finally, she believes that installation costs and tariffs are more important than solar irradiation for the economic dimension.

- Q2: Is the country overall ranking in agreement with what you would expect?
  - Expert 1: According to Expert 1, the final ranking obtained for the countries is in agreement with his expectation, in particular for Spain, Italy and Greece.
  - Expert 2: Yes. Since the judgement of Expert 2 is based on the current PV installed capacity, the compliance with the expected goals on RE, as well as the industrial level of the countries, he is in agreement with the results obtained.
  - Expert 3: Yes, and also highlighting that stakeholders influence is very important for all the countries, except for Greece. It is an expensive technology and the coordination of all the stakeholders that take part in some part of the supply chain is a key issue for the development of this sector. Regarding disposal and recycling, Belgium is the readier country with a great concern in the disposal technology and policies, in opposition to Greece. Other countries, like Spain, have the most advanced technologies for all processes,

however there is not sufficient support by governments.

According to the experts' answers and judgements, it emerges how they have similar as well as contrasting opinions which are combined together by the proposed framework in order to achieve a balanced and fair options ranking.

5.2. Managerial implications

The proposed MCDM framework and results have relevant managerial implications. Firstly, we provided decision makers with the main factors and sub-criteria to take into account to design a PV supply chain according to TBL. Moreover, the selected sub-criteria have been linked to the different stages in the PV supply chain. Secondly, the way the framework has been designed by means of AHP will provide the decision maker with a fast and easy tool for solving such a complex decision problem. The MCDM framework will allow the decision maker to rank and identify the most suitable locations for a sustainable supply chain in the PV sector. Finally, the framework will help decision makers to explore different scenarios based on the importance given to the three TBL dimensions. For example, the development of new European regulations might lead to prioritising social and environmental rather than economic targets.

6. Conclusions and future research opportunities

In this paper a MCDM framework based on AHP has been proposed to prioritise the factors characterising a sustainable supply chain in the PV sector and ultimately rank different suitable PV energy production locations. According to the TBL, social, economic and environmental factors have been taken into account as the main dimensions. Following a thorough literature review, the main stages of the PV supply chain and the sub-criteria affecting the main dimensions have been identified. Subsequently, the main dimensions and sub-criteria have been organised in a hierarchical structure according to AHP. Three experts in the PV sector have been asked to rate the sub-criteria against one another with respect to the corresponding dimension and then to rate seven main European countries with respect to each sub-criterion, following the AHP procedure. The ranking of sub-criteria and alternatives was computed and discussed.

Moreover, four different scenarios in terms of different combinations of importance given to the main dimensions (social, economic and environmental) were analysed, showing some remarkable differences in the ranking of the alternatives. Germany represents the highest rated alternative, while UK and Belgium the lowest in every scenario. Scenarios 1 and 2 show a very similar ranking for the considered countries, with the following order: Germany, Italy, Spain, France, Greece, UK and Belgium. Nevertheless, Greece becomes the third country and Italy the fifth option under the scenario 3, which is given when the economic dimension is considered the most relevant. With regard to scenario 4, which represents the highest weight given to the environmental dimension, France becomes the second most suitable alternative, followed by Italy, Spain and Greece.

This research may represent an initial step towards the design of a sustainable supply chain in the PV sector. Future research directions may include modelling the uncertainty of the judgement within the MCDM framework using fuzzy logic. Moreover, the proposed framework might be modified to address other decisions such as supplier or technology selection, as well as other sectors. Furthermore, once the most suitable country for developing a sustainable PV supply chain has been identified, a mathematical model based on quantitative information may be developed to make decisions regarding the actual design of the PV supply chain. Those decisions could *inter alia* concern in terms of facility location, supplier selection, technology selection, delivery and recycling options and could be directed at finding a desired balance of social, economic and environmental objectives.

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Appendix

Abbreviation	Definition
AHP	Analytic Hierarchy Process
AHP-OWA	Analytic Hierarchy Process with Ordered Weigh Averaging
ELECTRE	Elimination of Choice Expressing Reality
FMCGDM	Fuzzy multi-criteria group decision-making
GHG	Green House Gas
GIS	Geographical Information System
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MCDM	Multi-criteria decision making
MILFP	Multi-objective mixed-integer linear fractional program
MILP	Mixed integer linear programming
MULTIMOORA	Multi-Objective Optimisation by Ratio Analysis plus the full multiplicative form
O&M	Operation and maintenance
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
PVSC	Photovoltaic supply chain
RE	Renewable energy
RES	Renewable energy sources
SC	Supply chain
SSC	Sustainable supply chain
SSCM	Sustainable supply chain management
TBL	Triple Bottom Line
TOPSIS	Technique to Order Preference by Similarity to Ideal Solution
VIKOR	VIsekriterijumsko KOmpromisno Rangiranje

References

Abdallah, T., Diabat, A., Rigter, J., 2013. Investigating the option of installing small scale PVs on facility rooftops in a green supply chain. International Journal of Production Economics 146 (2), 465–477.

Ageron, B., Gunasekaran, A., Spalanzani, A., 2012. Sustainable supply management: An empirical study. International Journal of Production Economics 140 (1), 168–182.

Ahi, P., Searcy, C., 2013. A comparative literature analysis of definitions for green and sustainable supply chain management. Journal of Cleaner Production 52, 329–341.

Akgul, O., Shah, N., Papageorgiou, L. G., 2012. Economic optimisation of a UK advanced biofuel supply chain. Biomass and Bioenergy 41, 57–72.

Al-Yahyai, S., Charabi, Y., Gastli, A., Al-Badi, A., 2012. Wind farm land suitability indexing using multi-criteria analysis. Renewable Energy 44, 80–87.

Asgari, N., Hassani, A., Jones, D., Nguye, H. H., 2015. Sustainability ranking of the UK major ports: Methodology and case study. Transportation Research Part E: Logistics and Transportation Review 78, 19 – 39.

Aslam, T., Amos, H. N., 2010. Multi-objective optimization for supply chain management: a literature review and new development. In: Supply chain management and information systems (SCMIS), 2010 8th international conference on. IEEE, pp. 1–8.

Avril, S., Mansilla, C., Busson, M., Lemaire, T., 2012. Photovoltaic energy policy: Financial estimation and performance comparison of the public support in five representative countries. Energy Policy 51, 244–258.

Balfaqih, H., Al-Nory, M. T., Nopiah, Z. M., Saibani, N., 2017. Environmental and economic performance assessment of desalination supply chain. Desalination 406, 2 – 9.

Barboza, C., 2015. Towards a Renewable Energy Decision Making Model. Procedia Computer Science 44, 568–577.

Bazilian, M., Onyeji, I., Liebreich, M., MacGill, I., Chase, J., Shah, J., Gielen, D., Arent, D., Landfear, D., Zhengrong, S., 2013. Re-considering the economics of photovoltaic power. Renewable Energy 53, 329 – 338.

Bilimoria, S., Defrenne, N., 2013. The evolution of photovoltaic waste in Europe (May), 1–22.

Bowling, I. M., Ponce-Ortega, J. M., El-Halwagi, M. M., 2011. Facility location and supply chain optimization for a biorefinery. Industrial & Engineering Chemistry Research 50 (10), 6276–6286.

Campoccia, A., Dusonchet, L., Telaretti, E., Zizzo, G., sep 2014. An analysis of feed'in tariffs for solar PV in six representative countries of the European Union. Solar Energy 107, 530–542.

Carter, C. R., Rogers, D. S., 2008. A framework of sustainable supply chain management: moving toward new theory. International journal of physical distribution & logistics management 38 (5), 360–387.

Cavallaro, F., 2010. Fuzzy TOPSIS approach for assessing thermal-energy storage in concentrated solar power (CSP) systems. Applied Energy 87 (2), 496–503.

Chen, Z., Su, S. I. I., 2014. Photovoltaic supply chain coordination with strategic consumers in China. Renewable Energy 68 (February 2011), 236–244.

Crum, M., Poist, R., Carter, C. R., Liane Easton, P., 2011. Sustainable supply chain management: evolution and future directions. International journal of physical distribution & logistics management 41 (1), 46–62.

Cucchiella, F., D'Adamo, I., dec 2013. Issue on supply chain of renewable energy. Energy Conversion and Management 76, 774–780.

Cucchiella, F., D'Adamo, I., Gastaldi, M., Koh, S. L., Rosa, P., 2017. A comparison of environmental and energetic performance of european countries: A sustainability index. Renewable and Sustainable Energy Reviews 78, 401–413.

Davies, J., Joglekar, N., 2010. The market value of modularity and supply chain integration: Theory and evidence from the solar photovoltaic industry. Boston U. School of Management Research.

Davies, J., Joglekar, N., 2013. Supply chain integration, product modularity, and market valuation: Evidence from the solar energy industry. Production and Operations Management 22 (6), 1494–1508.

de Oliveira Moura Santos, L. F., Osiro, L., Lima, R. H. P., 2017. A model based on 2-tuple fuzzy linguistic representation and analytic hierarchy process for supplier segmentation using qualitative and quantitative criteria. Expert Systems with Applications 79, 53 – 64.

Dehler, J., Keles, D., Telsnig, T., Fichtner, W., Baumann, M., et al., 2015. Self-consumption of electricity from renewable sources. INSIGHT_e, Karlsruhe Institute of Technology.

DIA-CORE Project, 2016. Policy Dialogue on the Assessment and Convergence of RES Policy in EU Member States. Tech. rep.

Dusonchet, L., Telaretti, E., feb 2015. Comparative economic analysis of support policies for solar PV in the most representative EU countries. Renewable and Sustainable Energy Reviews 42, 986–998.

Dweiri, F., Kumar, S., Khan, S. A., Jain, V., 2016. Designing an integrated AHP based decision support system for supplier selection in automotive industry. Expert Systems with Applications 62, 273 – 283.

Elkington, J., 1997. Cannibals with forks. The triple bottom line of 21st century (April), 1–16.

Enbar, N., Weng, D., 2015. Budgeting for solar PV plant operations and maintenance: Practices and pricing. Tech. rep., Electric Power Research Institute.

European Commission, 1998. Environmental impact of photovoltaic technology. Tech. rep.

European Commission, 2010a. Communication from the Commission, Europe 2020. Tech. rep.

European Commission, 2010b. Europe 2020: A Strategy for smart, sustainable and inclusive growth. Working paper.

European Commission, 2012. The International Reference Life Cycle Data System (ILCD) Handbook. Tech. rep.

European Commission, 2016. Photovoltaic Geographical Information System (PVGIS). Tech. rep., European Commission. Joint Research Centre. Institute for Energy.
URL http://re.jrc.ec.europa.eu/pvgis/(accessed16.04.29)

European Commission, 2017. Strategic energy technologies information system. Tech. rep.
URL https://setis.ec.europa.eu/(accesed2017.01.03)

European Parliament, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009. Tech. Rep. 16.

European Parliament, 2012a. Directive 2012/19/EU of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE). Tech. rep.

European Parliament, 2012b. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency. Tech. Rep. October.

Eurostat, 2017. Share of renewable energy sources in final energy consumption. Tech. rep., European Commission.
URL http://ec.europa.eu/eurostat(accesed2017.02.8)

Fichera, A., Frasca, M., Palermo, V., Volpe, R., 2018. An optimization tool for the assessment of urban energy scenarios. Energy 156, 418 – 429.

Figueira, J., Greco, S., Ehrgott, M., 2005. Multiple Criteria Decision Analysis: State of the Art Surveys. Vol. 78. Springer-Verlag New York.

Freeman, J., Chen, T., 2015. Green supplier selection using an AHP-Entropy-TOPSIS framework. Supply Chain Management: An International Journal 20 (3), 327–340.

Gao, J., You, F., 2017. Design and optimization of shale gas energy systems: Overview, research challenges, and future directions. Computers & Chemical Engineering 106, 699–718.

Garcia, D. J., You, F., 2015. Supply chain design and optimization: Challenges and opportunities. Computers and Chemical Engineering 81, 153–170.

Garcia-Cascales, M. S., Lamata, M., Sanchez-Lozano, J., 2012. Evaluation of photovoltaic cells in a multi-criteria decision making process. Annals of Operations Research 199 (1), 373–391.

Gazibey, Y., Çilingir, F. C., 2012. Determining solar photovoltaic technologies to be focused in turkey using topsis method. In: 6th International Ege Energy Symposium & Exhibition, June. pp. 28–30.

Goe, M., Gaustad, G., 2014. Strengthening the case for recycling photovoltaics: An energy payback analysis. Applied Energy 120, 41–48.

Gonzalez de Durana, J. M., Barambones, O., Kremers, E., Varga, L., 2014. Agent based modeling of energy networks. Energy Conversion and Management 82, 308–319.

Govindan, K., Khodaverdi, R., Jafarian, A., 2013. A fuzzy multi criteria approach for measuring sustainability performance of a supplier based on triple bottom line approach. Journal of Cleaner Production 47, 345–354.

GRI, 2013. G4 sustainability reporting guidelines. Global Reporting Initiative, Amsterdam, Netherlands.

Hassini, E., Surti, C., Searcy, C., 2012. A literature review and a case study of sustainable supply chains with a focus on metrics. International Journal of Production Economics 140 (1), 69–82.

Honrubia-Escribano, A., Ramirez, F. J., Gómez-Lázaro, E., Garcia-Villaverde, P. M., Ruiz-Ortega, M. J., Parra-Requena, G., 2018. Influence of solar technology in the economic performance of pv power plants in europe. a comprehensive analysis. Renewable and Sustainable Energy Reviews 82, 488–501.

Hosenuzzaman, M., Rahim, N. A., Selvaraj, J., Hasanuzzaman, M., Malek, A. B. M. A., Nahar, A., 2015. Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation. Renewable and Sustainable Energy Reviews 41, 284–297.

Hutchins, M. J., Sutherland, J. W., 2008. An exploration of measures of social sustainability and their application to supply chain decisions. Journal of Cleaner Production 16 (15), 1688–1698.

IEA, 2015a. Key World Energy Statistics 2015. Tech. rep., International Energy Agency.
URL `https://www.iea.org/publications/(accessed16.05.31)`

IEA, 2015b. Trends 2015 in photovoltaic applications. Survey Report of Selected IEA Countries between 1992 and 2014. Tech. rep., International Energy Agency.
URL `https://www.iea.org/publications/(accessed16.05.29)`

IEA, 2015c. World Energy Outlook. Tech. rep., International Energy Agency.
URL `https://www.iea.org/publications/(accessed16.05.30)`

IEA, 2016. Snapshot of global photovoltaic markets. Tech. rep., International Energy Agency.
URL `https://www.iea.org/publications/(accessed16.06.2)`

Ignaccolo, M., Inturri, G., García-Melón, M., Giuffrida, N., Le Pira, M., Torrisi, V., 2017. Combining Analytic Hierarchy Process (AHP) with role-playing games for stakeholder engagement in complex transport decisions. Transportation Research Procedia 27, 500 – 507.

IPCC, 2014. AR5 Climate Change 2014: Mitigation of Climate Change. Tech. rep., Intergovernmental Panel on Climate Change.
URL https://www.ipcc.ch/report/ar5/wg3/(accessed16.05.12)

IRENA, 2012. Revewable energy technologies: cost analysis series. Solar Photovoltaic. Tech. rep., The International Renewable Energy Agency.
URL https://www.iea.org/publications/(accessed16.05.16)

Jäger-Waldau, A., Szabó, M., Scarlat, N., Monforti-Ferrario, F., 2011. Renewable electricity in Europe. Renewable and Sustainable Energy Reviews 15 (8), 3703 – 3716.

Kahraman, C., Kaya, I., 2010. A fuzzy multicriteria methodology for selection among energy alternatives. Expert Systems with Applications 37 (9), 6270–6281.

Kahraman, C., Kaya, I., Cebi, S., 2009. A comparative analysis for multiattribute selection among renewable energy alternatives using fuzzy axiomatic design and fuzzy analytic hierarchy process. Energy 34 (10), 1603–1616.

Kaya, T., Kahraman, C., 2010. Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: The case of Istanbul. Energy 35 (6), 2517–2527.

Kaya, T., Kahraman, C., 2011. Multicriteria decision making in energy planning using a modified fuzzy TOPSIS methodology. Expert Systems with Applications 38 (6), 6577–6585.

Keating, T., Walker, A., Ardani, K., 2015. Best practices in PV system operations and maintenance. Tech. rep., National Renewable Energy Laboratory (NREL).

Khalili-Damghani, K., Sadi-Nezhad, S., 2013. A hybrid fuzzy multiple criteria group decision making approach for sustainable project selection. Applied Soft Computing Journal 13 (1), 339–352.

Kucukvar, M., Egilmez, G., Tatari, O., oct 2014. Sustainability assessment of U.S. final consumption and investments: triple-bottom-line input–output analysis. Journal of Cleaner Production 81, 234–243.

Le Pira, M., Inturri, G., Ignaccolo, M., Pluchino, A., 2017. Modelling consensus building in Delphi practices for participated transport planning. Transportation Research Procedia 25, 3725 – 3735.

Lima-Junior, F. R., Carpinetti, L. C. R., 2016. Combining SCOR?? model and fuzzy TOPSIS for supplier evaluation and management. International Journal of Production Economics 174, 128–141.

Liou, J. J., Chuang, Y.-C., Tzeng, G.-H., may 2014. A fuzzy integral-based model for supplier evaluation and improvement. Information Sciences 266, 199–217.

Liu, J., Xu, F., Lin, S., 2017. Site selection of photovoltaic power plants in a value chain based on grey cumulative prospect theory for sustainability: A case study in northwest china. Journal of Cleaner Production 148, 386–397.

Luthra, S., Mangla, S. K., Xu, L., Diabat, A., 2016. Using AHP to evaluate barriers in adopting sustainable consumption and production initiatives in a supply chain. International Journal of Production Economics 181, Part B, 342 – 349.

Mangla, S. K., Kumar, P., Barua, M. K., 2015. Flexible decision modeling for evaluating the risks in green supply chain using fuzzy ahp and irp methodologies. Global Journal of Flexible Systems Management 16 (1), 19–35.

Mardani, A., Jusoh, A., Zavadskas, E. K., Cavallaro, F., Khalifah, Z., 2015. Sustainable and renewable energy: An overview of the application of multiple criteria decision making techniques and approaches. Sustainability 7 (10), 13947–13984.

Matulaitis, V., Straukaite, G., Azzopardi, B., Martinez-Cesena, E. A., 2015. Multi-criteria decision making for PV deployment on a multinational level. Solar Energy Materials and Solar Cells 156, 122–127.

Mota, B., Gomes, M. I., Carvalho, A., Barbosa-Povoa, A. P., 2015. Towards supply chain sustainability: Economic, environmental and social design and planning. Journal of Cleaner Production 105, 14–27.

Nikolaou, I. E., Evangelinos, K. I., Allan, S., 2013. A reverse logistics social responsibility evaluation framework based on the triple bottom line approach. Journal of Cleaner Production 56, 173–184.

Ossenbrink, H., Huld, T., Jager-Waldau, A., Taylor, N., 2013. Photovoltaic electricity cost maps. Tech. rep., European Commission. Joint Research Centre. Institute for Energy and Transport.

Owusu, P. A., Asumadu-Sarkodie, S., 2016. A review of renewable energy sources, sustainability issues and climate change mitigation. Cogent Engineering 3 (1), 1167990.

Paiano, A., 2015. Photovoltaic waste assessment in Italy. Renewable and Sustainable Energy Reviews 41, 99–112.

Pyrgou, A., Kylili, A., Fokaides, P. A., aug 2016. The future of the Feed-in Tariff (FiT) scheme in Europe: The case of photovoltaics. Energy Policy 95, 94–102.

Ramírez, F. J., Honrubia-Escribano, A., Gómez-Lázaro, E., Pham, D. T., 2017. Combining feed-in tariffs and net-metering schemes to balance development in adoption of photovoltaic energy: Comparative economic assessment and policy implications for european countries. Energy Policy 102, 440 – 452.

REN21, 2016. Renewables 2016. global status report. Tech. rep., Renewable Energy Policy Network for the 21st Century.

Saaty, T., 1980. The analytic hierarchy process. McGraw-Hill.

Saaty, T. L., 2008. Decision making with the analytic hierarchy process. International Journal of Services Sciences 1 (1), 83–98.

Sanchez-Lozano, J. M., Garcia-Cascales, M. S., Lamata, M. T., 2016. Comparative TOPSIS-ELECTRE TRI methods for optimal sites for photovoltaic solar farms. Case study in Spain. Journal of Cleaner Production 127.

Sanchez-Lozano, J. M., Henggeler Antunes, C., Garcia-Cascales, M. S., Dias, L. C., 2014. GIS-based photovoltaic solar farms site selection using ELECTRE-TRI: Evaluating the case for Torre Pacheco, Murcia, Southeast of Spain. Renewable Energy 66, 478–494.

Sanchez-Lozano, J. M., Teruel-Solano, J., Soto-Elvira, P. L., Garcia-Cascales, M., 2013. Geographical Information Systems (GIS) and Multi-Criteria Decision Making (MCDM) methods for the evaluation of solar farms locations: Case study in south-eastern Spain. Renewable and Sustainable Energy Reviews 24, 544–556.

Sarkis, J., Zhu, Q., Lai, K.-h., 2011. An organizational theoretic review of green supply chain management literature. International Journal of Production Economics 130 (1), 1–15.

Seuring, S., 2013. A review of modeling approaches for sustainable supply chain management. Decision Support Systems 54 (4), 1513–1520.

Seuring, S., Müller, M., 2008. From a literature review to a conceptual framework for sustainable supply chain management. Journal of Cleaner Production 16 (15), 1699–1710.

Solar Power Europe, 2019. Global Market Outlook for solar power 2018-2022. Tech. rep., Solar Power Europe.
URL http://www.solarpowereurope.org/(accessed19.05.12)

Sovacool, B. K., Lakshmi Ratan, P., 2012. Conceptualizing the acceptance of wind and solar electricity. Renewable and Sustainable Energy Reviews 16 (7), 5268–5279.

SPE, 2017. Global Market Outlook for solar power 2017-2021. Tech. rep., Solar Power Europe.
URL http://www.solarpowereurope.org/(accessed17.06.20)

Streimikiene, D., Balezentis, T., Krisciukaitien, I., Balezentis, A., 2012. Prioritizing sustainable electricity production technologies: MCDM approach. Renewable and Sustainable Energy Reviews 16 (5), 3302–3311.

Tao, J., Yu, S., 2015. Review on feasible recycling pathways and technologies of solar photovoltaic modules. Solar Energy Materials and Solar Cells 141, 108–124.

Troldborg, M., Heslop, S., Hough, R. L., 2014. Assessing the sustainability of renewable energy technologies using multi-criteria analysis: Suitability of approach for national-scale assessments and associated uncertainties. Renewable and Sustainable Energy Reviews 39, 1173–1184.

United Nations, 1998. Kyoto Protocol to the United Nations Framework. Tech. rep., United Nations.
URL http://unfccc.int/(accessed16.05.12)

Uyan, M., 2013. GIS-based solar farms site selection using analytic hierarchy process (AHP) in Karapinar region Konya/Turkey. Renewable and Sustainable Energy Reviews 28, 11–17.

Uygun, Ö., Dede, A., 2016. Performance evaluation of green supply chain management using integrated fuzzy multi-criteria decision making techniques. Computers & Industrial Engineering.

Ventre, G., Farhi, B., Szaro, J., Dunlop, J., 2001. Reducing the costs of grid-connected photovoltaic systems. Solar Forum.

Volpe, R., Frasca, M., Fichera, A., Fortuna, L., 2017. The role of autonomous energy production systems in urban energy networks. Journal of Complex Networks 5, 461 – 472.

WCED, U.N., 1987. Our common future. World Commission on Environment and Development. Oxford University Press.

Wee, H.-M., Yang, W.-H., Chou, C.-W., Padilan, M. V., 2012. Renewable energy supply chains, performance, application barriers, and strategies for further development. Renewable and Sustainable Energy Reviews 16 (8), 5451–5465.

West, J., Bailey, I., Winter, M., 2010. Renewable energy policy and public perceptions of renewable energy: A cultural theory approach. Energy Policy 38 (10), 5739–5748.

Wilding, R., Wagner, B., Abbasi, M., Nilsson, F., 2012a. Themes and challenges in making supply chains environmentally sustainable. Supply Chain Management: An International Journal 17 (5), 517–530.

Wilding, R., Wagner, B., Ashby, A., Leat, M., Hudson-Smith, M., 2012b. Making connections: a review of supply chain management and sustainability literature. Supply Chain Management: An International Journal 17 (5), 497–516.

Wilding, R., Wagner, B., Gimenez, C., Tachizawa, E. M., 2012c. Extending sustainability to suppliers: a systematic literature review. Supply Chain Management: An International Journal 17 (5), 531–543.

Wirth, H., 2016. Recent facts about photovoltaics in Germany. Tech. rep., Fraunhofer Institute for Solar Energy Systems ISE.

Wiser, R., Barbose, G., Peterman, C., 2009. Tracking the sun: The installed cost of photovoltaics in the U.S. from 1998-2007. Tech. rep., Lawrence Berkeley National Laboratory.

You, F., Tao, L., Graziano, D. J., Snyder, S. W., 2012. Optimal design of sustainable cellulosic biofuel supply chains: multiobjective optimization coupled with life cycle assessment and input–output analysis. AIChE Journal 58 (4), 1157–1180.

Yuce, B., Mastrocinque, E., Lambiase, A., Packianather, M. S., Pham, D. T., 2014. A multi-objective supply chain optimisation using enhanced bees algorithm with adaptive neighbourhood search and site abandonment strategy. Swarm and Evolutionary Computation 18, 71–82.

Yue, D., Slivinsky, M., Sumpter, J., You, F., 2014. Sustainable design and operation of cellulosic bioelectricity supply chain networks with life cycle economic, environmental, and social optimization. Industrial & Engineering Chemistry Research 53 (10), 4008–4029.

Yue, D., You, F., 2014. Functional-unit-based life cycle optimization of sustainable biomass-to-electricity supply chain with economic and environmental tradeoffs. Computer Aided Chemical Engineering 34, 651–656.

Zamboni, A., Bezzo, F., Shah, N., 2009. Spatially explicit static model for the strategic design of future bioethanol production systems. 2. multi-objective environmental optimization. Energy & Fuels 23 (10), 5134–5143.

Zhang, Q., Shah, N., Wassick, J., Helling, R., van Egerschot, P., 2014. Sustainable Supply Chain Optimisation: An Industrial Case Study. Computers & Industrial Engineering 74, 68–83.

Zhang, Y. H., Wang, Y., 2017. The impact of government incentive on the two competing supply chains under the perspective of corporation social responsibility: A case study of photovoltaic industry. Journal of Cleaner Production 154, 102–113.

Zimmer, K., Fröhling, M., Breun, P., Schultmann, F., 2017. Assessing social risks of global supply chains: A quantitative analytical approach and its application to supplier selection in the german automotive industry. Journal of Cleaner Production 149, 96 – 109.

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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.