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Risk-based methods for sustainable energy system planning: A review

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ABSTRACT

The value of investments in renewable energy (RE) technologies has increased rapidly over the last decade as a result of political pressures to reduce carbon dioxide emissions and the policy incentives to increase the share of RE in the energy mix. As the number of RE investments increases, so does the need to measure the associated risks throughout planning, constructing and operating these technologies. This paper provides a state-of-the-art literature review of the quantitative and semi-quantitative methods that have been used to model risks and uncertainties in sustainable energy system planning and feasibility studies, including the derivation of optimal energy technology portfolios. The review finds that in quantitative methods, risks are mainly measured by means of the variance or probability density distributions of technical and economical parameters; while semi-quantitative methods such as scenario analysis and multi-criteria decision analysis (MCDA) can also address non-statistical parameters such as socio-economic factors (e.g. macro-economic trends, lack of public acceptance). Finally, untapped issues recognised in recent research approaches are discussed along with suggestions for future research.

1. Introduction

Global investment in renewable energy (RE) in 2015 increased by 5% to $285.9 billion in relation to 2014, surpassing the last record of $278.5 billion in 2011 [1]. The annual increase in power capacity has also reached its highest level across all regions in 2015. Wind and solar photovoltaics (PV) account for an approximately 77% of new capacity, with hydropower accounting for most of the rest [2].

As the number of RE investments increases, so does the need to measure the associated risk and uncertainty from the perspective of different stakeholders throughout planning, construction and operational phases [3]. Energy developers, investors and policy makers face a future that implicitly involves technological, financial and political risks and uncertainties. Although, RE technologies potentially have a lower risk profile than conventional energy sources because they are disconnected from fossil fuel prices, they still entail considerable technological, financial and regulatory risk exposure, depending on the technology, country and regulatory regime. Fluctuation of cost components of power generation units, volatile crude oil prices,[1] electricity price and carbon costing in the context of the global climate change mitigation strategy, are examples of uncertainty components encountered by energy developers, investors and policy makers investors in the energy sector [4]. Often these risks are mitigated by governments in the form of price protection, but this can have a large budgetary burden, which often passes on to consumers through taxes and electricity bills [5].

Another stream of studies has focused on the identification and assessment of risks and uncertainty, as well as risk management solutions for sustainable energy projects [3,7,8,17–19]. In general, risk in the power generation investment sector is considered to be multi-dimensional and depends on the perspective of different stakeholders [9]. An array of analytical methods has been used to analyse various aspects of risk from the perspectives of different stakeholders. This results in a bewildering mix of studies that look at different sides of the same problem. However, there has been no systematic review of which techniques are most appropriate for reviewing individual, or groups of risks and how useful the outputs are to various stakeholders.

The aim of this paper is to provide an extensive, systematic literature review (SLR) of how risk and uncertainty has been analysed with respect to sustainable energy system planning. This will focus on identifying the attributes of risks (or modelled uncertainties) that each analytical method is most suited to address, as well as a critical comparison of the main outputs of such studies. The outputs of this review will map appropriate analytical techniques to specific risks, as

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[1] For example, international crude oil prices demonstrated dramatic changes from 2008 to 2009 (decreased by over 46%) as well as from 2009 to 2010 (increased by 25.6%, namely $60.4/barrel in 2009, $78.1/barrel in 2010) [161].

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well as comment on their application from the perspective of different stakeholders. The outputs are intended to provide a guide to researchers as to common practice in the assessment of risk and uncertainty for sustainable energy developments as well as indicating any possible gaps or new avenues for research.

The rest of this paper is set out as follows: Section 2 presents an overview of risk/uncertainty factors affecting investment decision-making in sustainable power generation planning and feasibility studies, along with an overview of the different perspectives among stakeholders. The risk-based evaluation methods are introduced in Section 3, and the cross-method comparison is conducted in Section 4. Finally, Section 5 summarises the findings of this work and suggests some focal points for future research.

2. Overview of risks and stakeholders' perspectives in sustainable energy generation systems

Risk in the power generation investment sector is generally considered to be multi-dimensional and depends on the perspective of different stakeholders. The "Comprehensive Actuarial Risk Evaluation – CARE" paper produced by the International Actuarial Association (IAA) provides a comprehensive taxonomy of risks faced by enterprises [9]. Among other classification schemes, the paper suggests a new perspective for risk categorisation into statistical and non-statistical risks. The former are the risks that can be measured or modelled with mathematical or statistical methods, such as stochastic modelling, while the latter are those that are difficult to model with existing knowledge.[2]

Risks associated with sustainable energy projects depend largely on a number of factors that are technology-, country- and regulatory-specific, while they also vary according to different stakeholders' perspectives. Authors working on risk identification, analysis and management in the sustainable energy investment sector have developed different risk categorisation schemes according to their intended focus. Table 1 summarises the most cited risks by employing a political, economic, social, technology, legal and environmental (PESTLE) approach.

Stakeholders involved in the field of RE investments comprise: project developers, project investors, insurers, manufacturers, consumers, affected local communities and policy makers. Each stakeholder tends to have different concerns and objectives from renewable energy investments. This means that risks will vary in importance across these different groups.

From a project developer's perspective, the objective is to make a sufficient return on investment (capital and other resources) through the sale of an RE project to an investor [12]. Investors are mostly interested in minimising risks of technical reliability, costs and risks of revenue disruption [14], while policy makers are concerned with designing efficient and effective policy schemes, which would provide the appropriate level of incentives to potential investors of RE projects that allow government targets to be met [15]. As such, risk analysis in RE projects has been performed in a generalised style covering numerous RES technologies and stakeholders' perceptions by some authors [6,16–19], while others distinguish risks through the related stakeholders' perspective (e.g. from the investor's and developer's view) [20] or by technology-specific risk factors [3,21].

3. Results of the literature review

Studies in this area tend to focus on the analysis of specific risk(s) from the perspective of a stakeholder or stakeholders. Therefore, the results section will map this research area in terms of which risks have been analysed by which methods and which stakeholders have been included.

3.1. Overview of the methods

The literature review was conducted on the basis of a SLR approach, which provides the synthesis of the research in a systematic, transparent, and reproducible manner, while also restricting the researcher's bias [22]. A description of the main steps followed to conduct the SLR approach is summarised in Appendix A. Analysis of the SLR results finds several methods used in the analysis of risk involved with sustainable energy generation systems. Table 2 provides a tally of how many times a paper using a particular method was identified by the systematic review process. This paper takes these methods forward for further analysis. As indicated in Appendix A, the total number of references considered for the review was 161 out of which, 113 originated from the SLR process, while the rest 48 references were identified through additional checks (e.g. via citation tracking or journal websites searching) in order to complement information on a particular topic which was not fully covered by the systematic review.

The review focuses on critically assessing which risks have been analysed by which methods, what are the common outputs of these methods and which stakeholders have been included in a number of widely cited representative risk-based methodologies applied in sustainable power generation planning and feasibility studies. These methods have been classified, for reasons of simplicity, into quantitative and semi-quantitative methodologies (see Fig. 1).

Quantitative risk-based evaluation methods deal with (statistical) risk factors that can be described by probability distributions. Widely cited methods falling into this category are: Mean-variance portfolio (MVP) theory, Real options analysis (ROA), stochastic optimisation methods, and Monte Carlo simulation (MCS). Semi-quantitative methods have the flexibility to take into consideration statistical and non-statistical risks. Semi-quantitative methods that were identified through the SLR are: MCDA and scenario analysis.

Table 3 matches the risk-based methods with risks/uncertainties as identified by the systematic review. The table can potentially provide guidance as to what methods are most suitable to address/model the specific risk and uncertainty factors listed.

3.2. Quantitative methods

3.2.1. Mean-variance portfolio analysis (MVP)

MVP is an established method of economic theory, based on the pioneering work of Harry Markowitz, who focused on the diversification of securities towards the construction of efficient portfolios, which would correspond to high expected return and low variance [97,98]. Later, Awerbuch [51] applied MVP for deriving optimal (or efficient) energy generation portfolios yielding maximum expected return in combination with minimised risk.

An energy generation portfolio constitutes a mix of generating assets put together to reduce total investment risks; as such, an efficient portfolio of energy generation technologies (with higher RE shares) reduces the threat of abrupt supply disruptions, hence reinforcing energy security through the mitigation of volatile fossil fuel price dependence.

Diversifying the power generation portfolio has been highlighted by a number of authors [18,20,99–102] as an effective strategy of risk hedging due to the creation of portfolio effects resulting in efficient power generating portfolios (i.e. optimum shares of different energy technologies in the portfolio resulting in a minimum level of risk towards attaining a given generating-cost objective). Diversification dimensions may be geographical, technological or value chain related. Numerous reports by international agencies, organisations, as well as

[2] Statistical risks include: market, credit, insurance, asset liability and liquidity risks, while examples of non-statistical risks are: reputational, opportunity, strategic, paradigm shift and black swan risks.