Energy 71 (2014) 130–136

Contents lists available at ScienceDirect

Energy

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

Methods for multi-criteria sustainability and reliability assessments of power systems

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ARTICLE INFO

Article history:
Received 10 January 2014
Received in revised form
8 April 2014
Accepted 14 April 2014
Available online 15 May 2014

Keywords:
Multi-criteria assessment
Sustainability
Reliability
Power systems

ABSTRACT

This paper reviews a published multi-criteria assessment of power systems and proposes new methods for normalization and ranking of criteria indicators. In previous work, the power systems are evaluated and ranked relative to the other systems considered in the assessment. This relative ranking system negatively affects the results in two ways. First, relative ranking tends to skew the results of the assessment, sometimes leading to incorrect conclusions and recommendations. Second, with a relative ranking system, the results lack applicability outside the assessment, since they are entirely dependent on the model from which they originate. This paper addresses these issues and proposes an extension that will combine experience curves, technological progress models, life cycle assessments, and thermodynamics within a dynamic multi-criteria optimization framework in order to create objective bounds for each sustainability indicator. This extension solves the relative ranking issue by creating a single system within which it is possible to rank and compare a variety of power systems, while maintaining relevant results between studies and over different scales. These results provide decision-makers with the information necessary to choose between systems to ensure a more sustainable future for the power sector.

1. Introduction

Due to the aging of power systems around the world and the institution of new environmental standards, such as Renewable Portfolio Standards in the United States, there is a growing need to update and improve power systems around the world. In order to ensure successful and meaningful improvements to these systems, and to determine which systems should be updated first, multi-criteria assessments may be utilized to inform power system decision-making. The results of such assessments provide researchers, power system authorities and government decision-makers with the information they need to design and develop the next generation of sustainable power system infrastructure.

This paper will review a recently published multi-criteria assessment of power systems and propose new methods for completing the assessment. The paper develops a model comprised of multiple quantitative indicators, which are calculated and combined in order to rank the systems. In the paper, a tendency is shown to rank alternatives according to the relative bounds of each indicator, as determined by the model itself.

While this may be a convenient method for completing an assessment, it is not without drawbacks. First, relative ranking tends to skew the results of the assessment, sometimes leading to incorrect conclusions and recommendations. Second, with a relative ranking system, the results lack applicability outside the assessment, since they are entirely dependent on the model from which they originate.

This paper addresses these issues and proposes an extension that will combine experience curves, technological progress models, life cycle assessments, and thermodynamics within a dynamic multi-criteria optimization framework in order to create MTBs (meaningful theoretical bounds), objective bounds for each sustainability indicator. The addition of MTBs solves the relative ranking issue by creating a single system within which it is possible to rank and compare a variety of power systems, while maintaining relevant results between studies and over different scales.

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http://dx.doi.org/10.1016/j.energy.2014.04.042
0360-5442/

This paper will proceed by presenting a critical review of multi-criteria assessments of power systems, identifying a clear gap in the existing literature. The new methods for normalizing indicators and ranking alternatives in multi-criteria assessments will then be explained and applied to the results from the first study. The final section will conclude and describe the implications of this work.

2. Sustainability and reliability assessment of microgrids in a regional market

Lo Prete et al. [1] present a multi-criteria sustainability assessment of microgrids in Northwestern Europe. The paper's goal to quantify sustainability and reliability with a set of metrics follows in the path of other multi-criteria assessments such as [2–4]. The assessment considered six power supply scenarios, in which three separate power systems were analyzed under two policy cases. Various metrics regarding the environmental, economic, technical, and reliability performance of each system were calculated, normalized, and ultimately combined to form a single index that allowed the systems to be ranked. A review of past work in this area is found in Ref. [5].

Lo Prete et al. utilize the COMPETES electricity generation modeling software [6] to construct a short-run network model of the Central Western European electricity market [1]. The network model results are then used to assess the systems level sustainability and reliability impact of installing residential fossil-fuel, or solar and fossil-fuel, MGs (microgrids) connected to the three Dutch nodes. Sustainability is measured as a combination of nine environmental, economic and social indicators, and reliability is measured with two separate indicators.

2.1. Methods

The model in Ref. [1] computes a short-run minimization of electricity generation, transmission, and distribution costs subject to non-negativity, generation and transmission capacity constraints, and current and voltage constraints. The optimization is run for six different scenarios, comprised of three installation possibilities – no MGs, fossil-fuel MGs, and PV (photovoltaic) and fossil-fuel MGs – each under two different CO_2 policies – no CO_2 price, and a price of 25 euros per ton. Capital costs for the installations are amortized over the life of the investments. A second model, which calculates two reliability indicators, LOLP (loss of load probability) and ELOE (expected loss of energy), is also run for each of the six scenarios. Each model is optimized for six representative hours, and extrapolated to a full year.

In the microgrid scenarios, the authors assume 50 separate MG installations, split between the three Dutch nodes, with each MG rated at 24 MW. The two microgrid architectures are comprised of 40% natural gas microturbines, 40% diesel reciprocating engines, and 20% of either SOFCs (solid-oxide fuel cells) or photovoltaics and lead-acid battery storage. In each case, combined heat and power systems are utilized, though additional heating capacity is needed in the photovoltaic microgrid, since PV does not contribute to heating supply. This difference produces a relative discount for fossil-fuel MGs, since the SOFCs, while only 20% of electric capacity, represent over 30% of the heating supply.

The results of the optimization – the costs and quantity of generation at each node – are then used to calculate eleven sustainability and reliability indicators that are used to rank each of the six scenarios. The indicators include CO_2, NO_x, and SO_x emissions, total cost with and without environmental externalities, electric energy and exergy efficiency and total system energy and exergy efficiency, and LOLP and ELOE. Once the indicators are calculated, the authors use various methods, taken from Ref. [3], to normalize each indicator so that all results appear as a number between zero and one. The indicators are then averaged so that each scenario receives a final composite score.

2.2. Findings and implications

The final results show that a price on CO_2 emissions marginally increases system cost, while improving all other operating parameters (i.e., decreasing emissions and increasing efficiencies). Scenarios that include a CO_2 price score higher than their no CO_2 price counterparts in each case. Microgrids are shown to provide significant sustainability and reliability benefits, and fossil-fuel based MGs provide the highest composite score. Microgrids that incorporate photovoltaics score low on the overall index primarily due to the high capital costs, but also due to the extra emissions generated by the additional heating capacity installed.

Even small penetration of microgrids in the model is shown to greatly increase reliability. The total installed capacity of MGs represents only 8% of total generation, though this small fraction improves system reliability by 28%. A post-index sensitivity analysis was then run by weighting each sub-index according to various potential user preferences. In each case, fossil-fuel MGs provided the greatest benefit over the legacy system. Additionally, it was determined that social considerations are not necessary since “the inclusion of a social sustainability index would not significantly alter the conclusions” [1].

Under current conditions, the model shows that fossil-fuel based microgrids provide efficiency, reliability and environmental benefits while also reducing total costs, although specific recommendations are difficult to consider due to the paper's limited scope and the assumptions made regarding microgrid placement and architectures. The authors assume the microgrids to be installed in residential areas, while also specifying the generation capacity and composition of the microgrid. This is done without optimizing size or generation for the specific locations being studied. For example, the authors choose to analyze PV driven MGs despite the fact that, as shown in Fig. 2, the Netherlands solar resource, at ~1100 kWh/m^2, is well below the European average of ~1400 kWh/m^2 [7]. As Fig. 3 shows, the same locations have wind resources, an average wind speed of ~7 m/s, that are well above the European average of ~5 m/s [8,9]. Future work in this area should utilize the published literature [10–16] to account for variability in renewable resources and technology by assessing the sustainability of various renewable-driven microgrids.

2.3. Discussion

While [1] successfully achieve the goal of utilizing diverse metrics to analyze the sustainability of various power systems, there are a series of concerns that must be addressed with regard to the paper's scope and methodology. First, the electricity network model is described as having 15 nodes and 28 transmission arcs, and while this construct is likely based on utility locations, the reader would benefit from a network graphic or a more detailed