Energy Policy 79 (2015) 127–149

Contents lists available at ScienceDirect

Energy Policy

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

Comparing the sustainability of U.S. electricity options through multi-criteria decision analysis

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HIGHLIGHTS

- Compares 13 electricity options across 8 sustainability criteria.
- Considers technical, economic, environmental, and social sustainability criteria.
- Examines tradeoffs under 10 representative decision-maker preferences.
- Includes policy implications for developing new electricity generation capacity in the US.
- Biopower and geothermal consistently rank high across several preference scenarios.

ARTICLE INFO

Article history:
Received 20 November 2014
Accepted 6 January 2015

Keywords:
Multi-criteria decision analysis
Sustainability
Renewable energy
Employment
Levelized cost of energy
Environmental life cycle assessment

ABSTRACT

Sustainable energy decision-making requires comparing energy options across a wide range of economic, environmental, social and technical implications. However, such comparisons based on quantitative data are currently limited at the national level. This is the first comparison of 13 currently operational renewable and non-renewable options for new US electricity generation using multi-criteria decision analysis with quantitative input values (minimum, nominal, and maximum) for 8 sustainability criteria (levelized cost of energy, life cycle greenhouse gas and criteria air pollutant emissions, land and water use, accident-related fatalities, jobs, and annual capacity factor) and 10 representative decision-maker preference scenarios. Results across several preference scenarios indicate that biopower and geothermal (flash and binary) currently score highest in sustainability for the US. Other renewable energy technologies generally offer substantial sustainability improvements over fossil fuel or nuclear technologies, and nuclear is preferable to fossil fuels in most scenarios. The relatively low ranking of natural gas combined cycle in most preference scenarios should encourage caution in adopting NGCC as a "bridge" to renewables. Although NGCC ranks high under economic and technical preference scenarios, renewables actually rank higher in both scenarios (hydro – economic; geothermal and biopower – technical).

1. Introduction

The term "sustainable energy" has become a popular catch phrase in recent years, akin to "green" or "clean" energy, and similar to these other terms, it often lacks proper definition and evaluation. One of the original and most influential documents in the growing field of sustainability science, commonly referred to as the Brundtland Commission Report, states, "A safe, environmentally sound, and economically viable energy pathway that will sustain human progress into the distant future is clearly imperative" (Our Common Future: Report of the World Commission on Environment and Development, 1987). More recent discussions continue to emphasize the importance of meeting growing energy needs of both present and future generations while addressing limitations in four main categories of

Abbreviations: ; CF, capacity factor; CSP, concentrated solar power; DR, discount rate; eq, equivalent; FF, fossil fuel; FTE, full-time equivalent; g, gram; GHG, greenhouse gas; GW, gigawatt; GWh, gigawatt-hour; GWy, gigawatt-year; HP, Harmonization Project; IAM, integrated assessment model; IPCC, Intergovernmental Panel on Climate Change; JEDI, Jobs and Economic Development Impact; kWh, kilowatt-hour; L, liter; LCA, life cycle assessment; LCOE, levelized cost of energy; m, meter; MB, minimal backup; MCDA, multi-criteria decision analysis; mg, milligram; MW, megawatt; MWh, megawatt-hour; NEEDS, New Energy Externalities Developments for Sustainability; NGCC, natural gas combined cycle; NREL, National Renewable Energy Laboratory; O&M, operation and maintenance; PV, photovoltaic; PWR, pressurized water reactor; TCD, Transparent Cost Database; TES, thermal energy storage; TWh, terawatt-hour

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http://dx.doi.org/10.1016/j.enpol.2015.01.007

sustainability: economic, environmental, social and technical (Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption; National Research Council, 2010; Sustainable Energy for All, 2014; Bob Everett et al., 2012). Yet, energy users and decision-makers still lack access to information that allows them to compare energy options across these categories.

Multi-criteria decision analysis (MCDA) is a quantitative tool that aids decision-makers in considering complex problems (including sustainable energy adoption), often with conflicting objectives and forms of data, taking into account the relative importance of different criteria without requiring monetization (Wang et al., 2009). Several recent studies have either conducted a formal energy MCDA (Akash et al., 1999; Diakoulaki and Karangelis, 2007; Kahraman et al., 2009; Maxim, 2013; Tsoutsos et al., 2009; Buchholz et al., 2009; Cavallaro, 2010, 2009; Dinca et al., 2007; Karagiannidis and Perkoulidis, 2009; Klein, 2013; Nixon et al., 2010; Scott et al., 2012) or provided a ranking of several energy options across a number of sustainability criteria (Evans et al., 2009; Jacobson, 2008). However, these studies have either not been specific to the US (Diakoulaki and Karangelis, 2007; Kahraman et al., 2009; Viebahn et al., 2008); have not included key sustainability criteria such as economic implications (Jacobson, 2008); or have focused on alternative technologies from only one energy source (Buchholz et al., 2009; Cavallaro, 2010, 2009; Dinca et al., 2007; Karagiannidis and Perkoulidis, 2009; Klein, 2013; Nixon et al., 2010; Scott et al., 2012). The MCDA conducted by Maxim (2013) is the most comprehensive energy analysis published to date, comparing 14 electricity generation technologies across 10 sustainability indicators at the global level. Additional analysis at the national and regional levels is needed to address the particular sustainability context of different global regions.

One challenge with conducting energy MCDA is compiling sustainability criteria data that cover the full life cycle of each option and are comparable across technologies. Recent efforts to “harmonize” environmental life cycle assessment (LCA) data (reduce variability by applying consistent assumptions) for individual electricity technologies, and in some cases across technologies for specific criteria (Fthenakis and Kim, 2010, 2009; Macknick et al., 2011; Meldrum et al., 2013) have increased the comparability of LCA estimates. However, sustainable energy decision-making requires comparisons between these environmental estimates and other sustainability criteria. Our study advances previous work in sustainable energy by integrating US-specific criteria data from each sustainability category in a MCDA framework to compare 13 electricity options under eight representative decision-maker preference scenarios. Energy decision-makers (i.e., policy-makers, utility managers, voters, business owners, residential consumers) may use this comparative analysis when considering national policy related to the development of new power plants. In addition, the quantitative data and analysis presented here lay the groundwork for future studies to engage energy decision-makers in developing and using interactive tools to consider important energy tradeoffs in future decisions.

2. Methods

MCDA generally involves four steps: (1) identify alternatives and sustainability criteria; (2) compile criteria data for each alternative in a comparable format; (3) calculate raw MCDA scores; (4) assign criteria preference weights, which indicate the relative importance of each criterion compared to other criteria, and rank alternatives. Our electricity alternatives (Table 1) include commercially-available technologies currently contributing to the US electricity generation mix: 39% coal; 27% natural gas; 19% nuclear; 7% conventional hydropower; 4% wind; 1% wood and wood derived fuels (woody biomass); 0.4% geothermal; 0.2% photovoltaic (PV) solar; and 0.02% concentrated solar thermal power (CSP). We also include offshore wind because it is commercially available in Europe; there are several demonstration projects in the US (Offshore Wind Research and Development, 2014); and there were sufficient data to include this technology. Many energy MCDAs do not define sub-technologies for their alternatives (i.e., referring to general solar (Akash et al., 1999; Kahraman et al., 2009; Kaya and Kahraman, 2010), solar PV (Begić and Afgan, 2007; Evans et al., 2009; Tsoutsos et al., 2009), solar thermal (Afgan and Carvalho, 2002; Madlener et al., 2007), geothermal (Evans et al., 2009; Kahraman et al., 2009; Kaya and Kahraman, 2010), without specifying the sub-technology in each of these categories). Since each sub-technology has unique sustainability characteristics, we added further technology specification wherever possible (Appendix A, Table A1) to reflect the most current technologies providing

Table 1
Electricity alternatives included in MCDA.

Electricity alternative	Specific technology[a]	Net rated capacity (MW)[b]
Biopower	Dedicated, direct combustion, stoke boiler, wet cooling	50
Coal	Pulverized, supercritical, wet cooling	600
Geothermal Binary	Hybrid cooling	50
Geothermal Flash	Hybrid cooling	50
Hydropower	Conventional, reservoir	500
NGCC	Natural gas combined cycle, wet cooling	400
Nuclear	Pressurized water reactor (PWR), boiling water reactor (BWR), Gen III, wet cooling	1175
Offshore wind	Fixed bottom	100
Onshore wind	Not specified further	100
Solar CSP–FF	Concentrated solar power (CSP) parabolic trough with fossil fuel (FF) energy backup (6 h of energy backup for nominal value; 1–12 h for minimum/maximum), wet cooling	100
Solar CSP–MB	Minimal energy backup (MB: electricity and fossil fuel for startup, shutdown, parasitic electrical loads, heat transfer fluid freeze protection), wet cooling	100
Solar CSP–TES	Molten salt thermal energy storage (TES) (6 h of energy backup for nominal value; 1–12 h for minimum/maximum), wet cooling	100
Solar photovoltaic (PV)	Mono-crystalline and/or poly-crystalline silicon, utility-scale, flat panel	5

[a] The specific technologies defined here were not available in all sustainability criteria data sources. Table A1 provides more specific information about which sub-technology was selected for each data source.
[b] Median value for net rated power capacity from National Renewable Energy Laboratory Transparent Cost Database (NREL, 2012). The full range of capacity values is presented in Table A2.