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Sustainability Assessment of Complex Energy Systems Using Life Cycle Approach- Case Study: Arizona State University Tempe Campus

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Abstract

Solar PVs are widely proposed as sustainable alternatives to electricity generation from fossil fuels to fulfil the ever-growing energy demands. They have demonstrated great potentials to mitigate devastating environmental impacts of power generation; but, is it enough for a sustainable development? The aim of this paper is to provide a better understanding of how large scale deployment of solar power generation would affect sustainability of a community energy infrastructure. Along with site-specific environmental impacts, cost and social dimensions of sustainability are also considered throughout the life cycle of energy systems and fuels. The proposed framework acknowledges different perspectives and captures the complexities and limitations of power generation.

We developed a multi-criteria sustainability appraisal framework to evaluate and compare the sustainability of two different fuel mix scenarios. In this study, accountability of the energy system as well as the safety and resource depletion issues are included as Social Impacts by introducing proper indicators. Assessment results indicated that solar PVs performance has to be improved in cost and social sustainability criteria. The paper also explores the challenges and complexities of sustainability evaluation of energy systems and identifies the bottlenecks of solar PVs deployment in large scales. We concluded that the rate of large-scale penetration of photovoltaics with the purpose of sustainability enhancement should be addressed by adaptive management approaches examining energy demands, solar PV manufacturing and efficiency improvement trends.

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Keywords: sustainability, energy Infrastructure, fuel mix, solar PV penetration, life cycle sustainability assessment, adaptive management

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1. Introduction

Moving toward sustainability necessitates balance among stakeholders, society, and environment. Achieving this goal requires exploring for solution spaces from different perspectives to ensure balanced development in all areas, and not just one. Therefore, considering sustainability as a design goal for decision makers, a complex problem fraud with uncertainty and multi-dimensionality must be addressed. In this regard, sustainability assessment tools are proposed try to overcome such complexities stem from interconnectedness of systems and society, account for different legitimate perspectives, and facilitate comparing and communicating.

Regarding power generation, more environment-friendly (green) energy resources and technologies are needed to diminish the adverse effects on nature. But, energy infrastructures are strategic, socio-economic systems which their performance is limited within technological boundaries. Solar PVs are widely proposed as sustainable alternative to common electricity generation methods to fulfill the ever-growing energy needs in order to mitigate greenhouse gas emission, air pollution, and devastating effects on natural resources. Many researches, have been done to evaluate and document GHG emissions of different types of photovoltaics [1], and other power plants [2], [3], [4] through their life cycle.

The other category of sustainability assessment researches provides wider and multiple views supporting multi-dimensional decision making. Fthenakis et al. investigated environmental, health and safety issues during solar panel manufacturing process capturing some environmental and social sustainability aspects [5]. Mason et al. investigated large scale solar photovoltaics deployment life-cycle CO2 emission and payback time addressing part of environmental and cost aspects of sustainability [6].

Energy production sustainability assessment researches which cover all sustainability criteria are scarce; Roth et al. and May et al. assessed and compared sustainability of various electricity generation technologies of a major Swiss utility and Australians fossil fuels respectively [7] and [8]. Karger et al. studied the decentralized electricity generation advantages and disadvantages by comparing four future scenarios for Germany according to overall sustainable development concepts [9]. Phillips et al. explored sustainability of large-scale photovoltaic power plants during installation and operation phases [10]. Most of this literature argue that replacing conventional fossil fuel-based electricity generation by solar PVs would result in huge environmental benefits. Although such analyses are essential for comparing the environmental impacts of electricity generation facilities, they lack two basic features in order to be used by decision makers for sustainable development planning: (a) fail to approach the energy crisis from multiple perspectives and therefore neglect the inherent technological and socio-economic complexity of energy systems (b) view the electricity generation as individual power plants and methods while in practice, it is comprised of various fuels and facilities working together as complementary systems. Therefore, large scale solar power benefits, such as “reduced transmission lines from the electricity grids” and “increased energy interdependence at the regional and/or national level” [10], cannot be ensured unless electricity production scenarios within the real technological and socio-economic constraints to be considered taking the Life Cycle Sustainability Assessment (LCSA) approaches.

In this paper, we elaborate the complexities and practical difficulties of sustainability assessment of energy infrastructure at community level; a multi criteria sustainability assessment framework, accounting for site-specific environmental, cost and social impacts is developed. Comparing two energy mix scenarios for 2025, the proposed appraisal would help decision makers to identify challenges associated with large solar PV penetration, and adaptively manage the energy infrastructure sustainable development. We also argue that, when energy systems are targeted, reliability and safety issues must be considered within the sustainability appraisal framework.

2. Methods

In this section, energy infrastructure sustainability assessment methods and metrics developed in this study are explained. By defining more practical and quantitative metrics, we try to provide better understanding of how large scale deployment of solar power generation would improve ASU Tempe campus sustainability. For this purpose, two different scenarios are considered: Business as Usual (BAU) and Climate Neutrality Roadmap (CNR).

2.1. System Definition and Boundaries

The power production facilities, either on-site or utility provider power plants, implemented to cover electricity demands of ASU Tempe campus are considered in this study. The system boundaries for assessing climate neutrality is wide enough to include even air travels which account for 37 percent of GHG emissions [11]. Same approach for sustainability assessment of solar PV implementation will result in comprehensive sustainability assessment. In order to achieve this goal, system boundaries are defined to include the whole life cycle of energy resources enabling us to account for all environmental, cost, and social impacts of various power generation methods from cradle to grave.

2.2. Sustainability criteria

In this particular problem, we intend to compare the sustainability of two different electricity generation mixes by applying the LCA approaches through all aforementioned sustainability criteria. This kind of approaches can be considered Life Cycle Sustainability Assessment which comprises LCA techniques, to measure environmental impacts, LCC (Life Cycle Costing), that explores costs throughout the whole life of the materials and systems, and also the social dimensions.

Deciding sustainability metrics should be accomplished in the context of the problem. Environmental impacts and resource allocation in power generation problems are inseparable parts. On the other hand, knowing that we are applying renewable energy resources (sun) for a university campus, social perspectives of sustainability can be restricted to system/resource accountability and safety issues. Implementation of solar PVs will certainly bring up cost and benefit controversies; therefore, considering cost as one major sustainability criteria is inevitable and using the LCC we will be able to account for all the cost impacts throughout the life cycle. Therefore, in this study, three sustainability criteria are investigated: Environmental Impacts (En): indicating GHG emissions, water pollution, air pollution and how much material, energy and water is being used– Costs (Co): including initial, operational and maintenance costs – Social (So): including life cycle safety assessment and system accountability under normal conditions. Energy systems, which are classified as critical infrastructures, cannot be considered sustainable if not be reliable enough. Sustainability metrics of all three sustainability pillars are listed in Table 1 along with the points and weighting factors assigned to each power generation system. Points are calculated using normalized data on systems performance gathered from literature. Metrics should be defined in a way which enables comparison between solar and traditional power generation methods. In other words, metrics should be defined so that can be assessed for all power generation systems and have same units. It worth mentioning that score of 1 does not mean that there is no negative impact, but only indicates that the system has the best performance among investigated electricity generation technologies.

For each criteria and power generation system, the (single-criteria, single-system) sustainability is defined as:

$$En = \frac{\sum_{i=1}^{n} c_i * En_i}{\sum_{i=1}^{n} c_i} \tag{1}$$

Where c_i is the i^{th} metric weight and En_i is the i^{th} metric score. Thus, each criteria sustainability performance index (En, Co, So) will be bound between 0 and 1; by assigning different weights to each metric, we will be able to find out how the system operates based on the relative importance of each metric. Metric weights might be different in different regions or countries based on social, economic, and geographical situations; for example, Land Use might be valued higher in New York than in Arizona. Extensive literature review is needed to find the relative importance of sustainability metrics within each criteria, prioritize them, and score them based on the system under investigation.

2.3 System Alternatives

In order to compare the sustainability of ASU Tempe campus energy system in 2025, two different energy mixes are defined: Business As Usual (BAU) and Climate Neutrality Roadmap (CNR). Monitoring energy demands and solar power generation capacity from Sep.2013 to Sep.2014 shows that campus solar panels can reduce the net demand by up to %42; but, based on overall building energy consumptions and solar generation actual data, gathered from ASU energy manager (to account for solar panels capacity factor), we found that solar PVs can only provide %13.3 of the demands annually. Therefore, for BAU energy mix of ASU consumption, the actual mix comprises of %13.3 on-site solar generation, and we assumed that all the APS (the utility provider) fuel mixes decrease proportionally. The calculated fuel mix is illustrated in Figure 1.

Table 1- list of sustainability metrics for electricity generation and assigned points

Impact Category	**Coal**	**Gas**	**Nuclear**	**Hydro**	**Solar**	**Weight Factor**
Environmental (*En*) Impacts						
Materials						
Lifespan	0.4	0.2	0.6	1	0.2	2
Energy						
Energy Returned per Energy Invested (EREI) [12]	0.8	0.1	0.5	1	0.068	2
Water						
Water Consumption [13]	0	0.83	0.86	1	0.79	3
Land						
Land Use [12]	0.3	0.78	0.99	0.96	0.98	1
Pollution						
Human Toxicity (Cancer) [12]	0.04	0.95	0.99	1	1	3
Human Toxicity (non-Cancer) [12]	0.07	0.93	0.97	1	1	2
Ionizing Radiation [12]	0.98	0.98	0.04	1	1	1.2
Respiratory Inorganics [12]	0.09	0.95	1	1	1	1
Fresh Water Ecotoxicity [12]	0.17	0.93	0.98	0.99	1	1
Fresh Water Eutrophication [12]	0	0.97	1	1	1	1
Marine Eutrophication [12]	0.15	0.91	1	1	1	1
Water Thermal Pollution	0	1	1	1	1	1
Climate Change						
GHG Emissions	0	0.4	0.98	0.98	0.96	2
Cost (*Co*)						
Operational/Maintenance Costs						
Operational Costs [13]	0.53	0	0.91	0.72	1	2
Maintenance Costs [13]	0.16	0.81	0.18	0.86	1	1
Government Subsidy (FITs, tax credits etc.)	0	0	0	0	1	0.2
Insurance Cost	1	1	1	1	0	0.1
Initial Costs						
Initial Costs [13]	0.4	1	0.38	0.31	0.56	3
Initial Cost Trend	0	0	0.6	0	1	0.5
Social (*So*) Impacts						
Resource Scarcity [12]	0.65	0.9	0.68	0.97	0.985	1.5
Safety [1]	0.5	0.8	0	0.8	0.6	2
Accountability in different weather conditions	1	1	1	0.95	0	3

1- Safety issues associated with mining, manufacturing, and during operational life.

One of the difficulties of accurately assess the sustainability, is the diurnal changes of electricity generation fuel mix, when peaker plants shut off and on regularly during on-peak and off-peak hours. Fuel mixes are also changes year by year based on the price and availability of the fuels [14]. To simplify the problem, we assume that the APS fuel mix is constant during time.

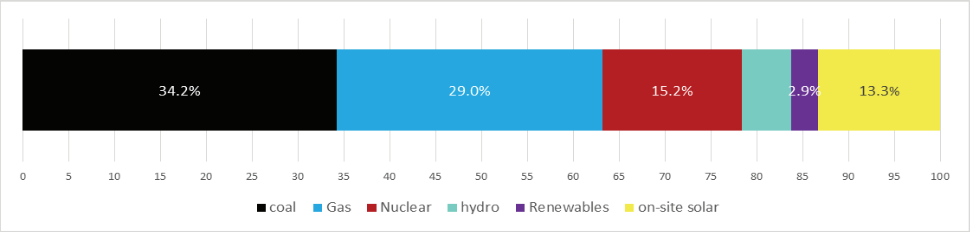

Fig 1. BAU scenario fuel mix for ASU Tempe Campus

Based on the ASU neutrality roadmap, by 2025, building energy consumptions will be increased by %25 (due to campus expansion) considering all the new construction, deep energy retrofits, deep retrofits over time, cross-cutting measures which will help the campus save considerable amount of energy [11]. On the other hand, based on the renewable energies implementation strategies, ASU will double the installed solar PVs by 2025. We assumed that the electricity generation mix of APS remain constant. Therefore, considering the demand increase, efficiency measures, and implementation of more solar panels, energy consumption mix of ASU Tempe campus at 2025 will be like what is shown in Fig .

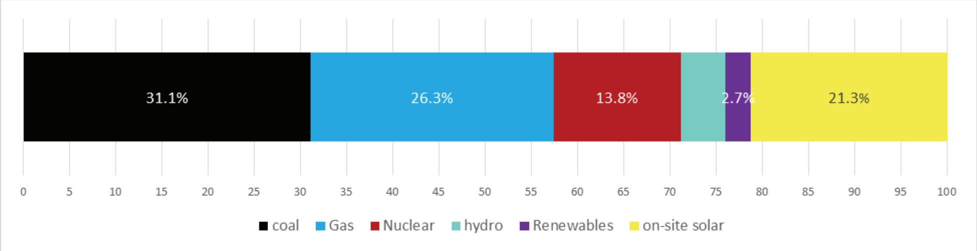

Fig 2. CNR scenario fuel mix for ASU Tempe Campus in 2025

Now, single-criteria sustainability performance index for each scenario (En_m, Co_m, So_m) can be calculated using single-criteria, single-system sustainability performance (En, Co, So found from equation 1):

$$En_m = \sum_{j=1}^{k} m_j \,.\, En \qquad (2)$$

Where m_j the j^{th} fuel percentage and k is the number of different fuels/technologies in the mix.

2.4 Sustainability Index (SI) Calculation

As mentioned before, all three sustainability criteria, known as triple bottom line, are considered in this study. In the following, some of the indicators and assigned scores and weight factors are discussed:

Environmental Impacts: In this category, most of the metrics are straightforward and required data can be obtain from the literature. Based on the obtained information, solar panels almost has no emission during their operational life [15]. Hazardous materials release during manufacturing process and particular situations are explored in social impacts which focus on safety, system accountability and manufacturing conditions. Regarding climate change devastating effects, nuclear power plants has the least GHG emissions through the life cycle (17 t CO2e/GWh) followed by hydro plants with 18 t CO2e/GWh. Solar panels rank 3rd with 39 t CO2e/GWh emission [16]. APS has three coal power plants, Four Corners located at New Mexico, Cholla and Navajo, located at northern Arizona. Among these, Four Corners plant cooling water needs are provided by Morgan Lake and Navajo is operated by Salt river project. Knowing that a typical 600-MegaWatt plant will increase the cooling water temperature by up to 20-25◦F, APS coal-fired plants will definitely contribute to water thermal pollution which can be harmful for the ecosystem. APS nuclear and natural gas power plants use treated effluents as cooling water; therefore, for calculating water consumption, we considered the natural gas plant to be no-cooling type. For the nuclear plant required water, we only took the enrichment water consumption into account. In addition, no thermal pollution is considered for natural gas and nuclear power plants.

Cost: based on Edgar and Adisa 2014 [17], hydro power plants has the highest initial costs with 2130 $/kW and natural gas has the least with 662 $/kW initial cost. Solar PV panels are the second least expensive with 1190 $/kW. "Initial cost trend" is the other important cost indicator that considered in this report. Coal, Natural Gas and other fossil fuels are getting more and more expensive due to their environmental impacts and scarcity. On the other hand, third generation of nuclear power plants are evolving and are likely to be effective around 2020; this will lessen the initial costs of nuclear electricity generation. Therefore, we considered a positive trends in initial costs of nuclear power plants. Renewable energies are not yet fully developed, and due to Neji, 2008 [18] noticeable improvements in their efficiency enhancement and cost reduction is expected in the future which make them more competitive.

Operational costs of solar panels are almost zero; they also has the least maintenance costs around 12.12 $/kW.

Coal and Nuclear power generation are the most expensive ones with 76.54 and 69.06 $/kW of maintenance costs respectively [13]. Some federal governments provide incentives in form of tax discounts to encourage solar power implementations. On the other hand, solar PVs may impose some extra costs for insurance due their fragility. These kind of benefits and drawbacks are considered by defining proper cost metrics and weight factors.

Social Impacts: capturing social impacts of energy infrastructure is the most challenging task among various sustainability criteria. In this study, "safety" in all life cycle stages, "accountability in various weather conditions", and "resource scarcity" are considered as social dimensions of electricity generation systems. Regarding safety issues, extensive statistical analysis is needed to identify risks associated with raw material mining, accidents happen to workers during manufacturing and power plant operation, etc. As mentioned before, severity of the accidents, number of people that potentially might affected, and probability of happening are considered and different generation systems were scored accordingly.

Risks associated to energy resources are those hazards which threat workers and people. Coal mining catastrophes are widespread across the world and include suffocation, gas poisoning, roof collapse and gas explosions. During the past decade, averagely 26 miners' deaths per year has been reported. In Natural Gas power generation system, fires are among the most common events and radiative pollutions are the most catastrophic risk of nuclear plants. Hydro power plant failures are rare but endangers the surrounding villages and cities. Solar panels also release considerable amount of Cadmiums, which may cause serious lung problems, if fire happens. Based on National Renewable Energy Laboratory (NREL) [19], workers at Solar PV panel manufacturing factories are at risk of inhaling Silicon dust, and other heavy metals.

Fossil fuel resource depletion will limit coal and natural gas fired power plants development when solutions to sustainable development are desired. On the other hand, diurnal and long-term climate changes would affect power generation systems performance; for instance, fluctuations in electricity generation of solar photovoltaics during cloudy days, reduces accountability of the energy systems. Other social metrics such as, job creation, customer preference, grid stability and robustness are ignored in this paper due to lack of data and quantitative indicators.

3. Results

The aim of this study is to evaluate and compare the sustainability of two different electricity generation fuel mixes for Arizona State University Tempe campus in 2025. Taking the LCSA (Life Cycle Sustainability) approaches, all sustainability dimensions, i.e. environmental, cost, and social effects are assessed throughout the whole life cycle of power generation systems and fuels. Environmental impacts are captured using proper indicators which scored based on particular conditions and locations of power plants.

Having all sustainability indicators scored, the Sustainability Index was found by simply averaging the single-criteria sustainability indices (results shown in figure 3) calculated using equation 2. By definition, a sustainable system is the one that can stay balanced among various sustainability criteria. Therefore, in this study, we suggest taking the variance into account; if two competing alternatives have the same Sustainability Index, the one with smaller variance would be considered more sustainable. In this study, weighting factors are assigned intuitively considering relative importance of sustainability indicators and site-specific importance (for example, water consumption is more important than land use in arid regions).

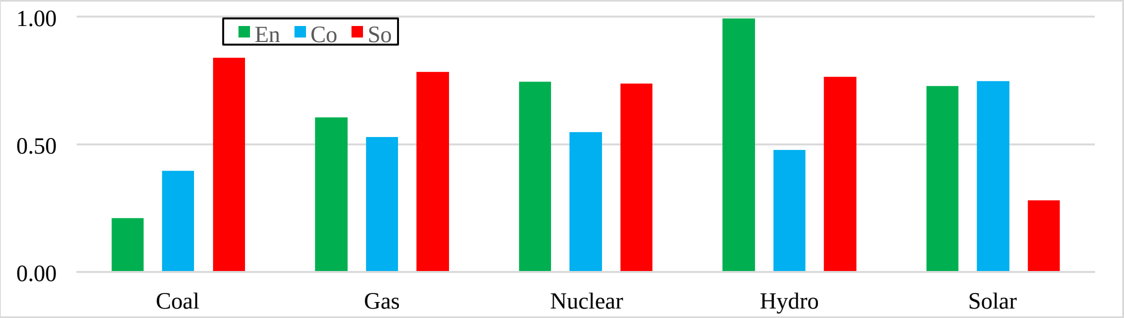

Figure 3- Sustainability performance of electricity generation technologies

As depicted in figure 3, solar PVs has acceptable environmental and cost impacts while their performance in social criteria has to be improved. Sustainability Index calculation for two competitive scenarios, considering equal weights for environmental, cost, and social criteria, shows only %0.2 improvement (BAU SI = 0.571 and CNR SI = 0.573). Therefore, solar power can be considered as an environmentally friendly alternative to fossil fuels but not a sustainable one due to their poor safety and accountability. Sustainability enhancement potentials of solar PVs has overstated by neglecting various social, cost, health and environmental issues associated with pre-operational and recycling processes.

Although solar and hydro power plants can be considered as green energies, they cannot contribute much in power generation mix due to grid stability and capacity factor issues. More than %55 of the electricity generation fuel mix is comprised of coal and natural gas and therefore the overall Sustainability Index is mostly influenced by performance of these power plants.

4. Discussion and Future Works

In most of the sustainability assessment studies, the main focus is on environmental impacts. Electric energy generation is composed of many different power plants; they consume different fuels, emit different amount of GHGs, dispose different kinds and amounts of waste, and generate electricity with different efficiencies. In addition, the combination of fuels used by a particular supplier varies across the country. Therefore, such differences should be considered in sustainability evaluations as well as the site-specific effects. Furthermore, the fuel mix varies based on demands temporal changes. Knowing that each of fuels and methods of electric power generation has their own emissions, environmental impacts, and expenses, sustainability of energy infrastructure is changing all the time. This makes the sustainability assessment more complicated. In this report, diurnal and seasonal electricity generation mix variations are ignored and annually averaged combinations are considered.

Different power plants take different roles in supplying electrical energy based on their capabilities and technical limitations. Baseload power plants run continuously and just shut down during overhauls or in emergency conditions. They are responsible for supplying all or part of the continuous energy demand. Low cost fuels and systems, relative to other available options, are usually implemented as baseload plants; nuclear and coal-fired plants are typical for this purpose. One of the issues regarding these plants is that it takes several days to shut down and start up; that is, the growth rate of solar PVs deployment is limited based on how flexible other electricity generation plants are (known as duck curve problem).

Reliability of the energy systems while undergo a natural or manmade disturbance is also crucial to their sustainability. Therefore, robustness, as system resistance to disturbances, and resilience, as the systems’ ability to recover from total or partial failures, also can be considered as social characteristics of sustainable energy infrastructure as it tightly coupled with social welfare. Quantifiable yet simple indicators are needed to address robustness and resilience as sustainability metrics. These features will be addressed in future studies.

It can be concluded that, system boundaries are extremely important for sustainability assessments to help planners and decision-makers to identify all consequences of a particular action. In order to improve the sustainability of energy infrastructures, technically feasible system alternatives, in contact with environment and society, and considering all economic impacts throughout the whole life cycle of subsystems should be evaluated. Sustainable development, as the pathway to achieve sustainability, entails balanced environmental, economic, and social performance improvements.

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