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Interactions of factors impacting implementation and sustainability of renewable energy sourced electricity

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A R T I C L E I N F O

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Two renewable energy sourced electricity (RES-E) technologies are at the forefront of the current energy transition away from fossil fuels: wind, and solar photovoltaic. However, RES-E must overcome implementation, and sustainability challenges from factors identified in economic, policy, societal, technological, and environmental dimensions. RES-E diffusion is also a complex problem, and this critical review suggests that outcomes depend on interdependencies between factors within a single, or across multiple dimensions. Four categories of interactivity have been identified. Higher capital costs or market inequalities associated with the economic dimension of RES-E drive supportive policies or incentives in the policy dimension. In the policy-policy category, interactions between RES-E demand or supply side incentives influence electricity pricing, energy market mixes, or greenhouse gases emissions. The society-technology category examines societal-technological interactions at both micro, and macro scales. The environment-technology category details interactions between RES-E and the environment. The technology-technology category examines synergies between RES-E when collocated with conventional electricity generation technologies

This review identified several knowledge gaps. First, research on RES-E implementation lacks system level analyses on the impact of interactions on project outcomes. A well-developed line of research examines interactions between multiple, simultaneous supportive policies on RES-E implementation in developed nations, however, a second gap exists on the understanding of these interactions in developing nations. A third gap exists on evaluating the impact of technological lock-in. This includes the impact on RES-E implementation rates when the complex economic, policy, governance, and societal factors implicated in lock-in are removed.

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Abbreviations: CCS, Carbon capture and storage; CO_2, Carbon Dioxide; CSP, Concentrating solar power; CTS, Cap and Trade schemes; ETS, Emissions trading (EU); EU, European Union; FIT, Feed-in-tariff; GO, Guarantee of origin; NIMBY, Not-in-my-backyard; PV, Photovoltaic solar cell; RES-E, Renewable energy sourced electricity; RPS, Renewable energy portfolio standard; TGC, Tradable green certificates; TWC, Tradable white certificates

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1. Introduction

Global energy demand has doubled in the last 50 years, and is forecast to rise an additional 45% by 2030 [1]. The dominant energy supply used to meet this need is fossil fuels [2]. However, fossil fuel combustion is responsible for negative environmental impacts that include air pollution, acid rain, and anthropogenic greenhouse gas (GHG) emissions [3]. Relying on these fuels to meet a growing energy demand will only accelerate environmental degradation. Recognizing the importance of transitioning the global energy supply away from fossil fuels, a number of renewable energy sources are used to meet society's energy needs.

Traditional biomass is the single largest source of renewable energy, with close to 2.7 billion people relying on firewood or dung for heating and cooking needs [4]. The next largest share of renewable energy capacity is renewable energy sourced electricity (RES-E) generation [5,6]. Global interest in RES-E is increasing for two reasons; decarbonizing electricity production is considered one strategy to address climate change, and electricity demand is projected to increase up to 80% by 2040 [7]. Three technologies dominate RES-E production: hydropower, wind, and solar photovoltaic (PV) [5].

Hydropower generates the greatest share of RES-E capacity. It also has the ability to store, and then release water as needed. This allows electricity production to meet base demand, a distinct advantage over wind, and solar technologies where RES-E generation varies with environmental conditions. In spite of the challenges integrating environmentally variable RES-E production into existing electricity production systems, both wind, and PV capacities have increased significantly in the last decade [5]. This trend is expected to continue, with both technologies projected to supply significant portions of future global energy demand [5,8]. However, these technologies must overcome challenges to both implementation, and post-implementation sustainability.

Developed and developing nations face distinct challenges. In developed nations, several factors slow implementation rates. One is market competition between the higher capital cost of RES-E compared with traditional fossil fuel based electricity [2]. The second factor is market inequalities resulting from inaccurate pricing of fossil fuel energy production. These occur when fossil fuels are either heavily subsidized [9], or the full costs of negative environmental impacts are not accounted for [5]. Another factor is resistance from fossil fuel business and political interest groups to the RES-E transition [10].

Addressing challenges to RES-E transition in developing nations is particularly critical. In the next two decades, the majority of increased energy demand will occur in these countries [11]. Their continued reliance on fossil fuels to meet future energy needs will significantly impact GHG emissions [12]. Recognizing the importance of developing nations in climate change mitigation, significant economic resources have been invested in RES-E implementation. However, many well designed technologies fail prematurely for both technical and non-technical reasons. This is a systemic problem affecting between one-quarter to one-third of the implemented projects, irrespective of implementing agency [13,14]. In addition to challenges mentioned above, developing nations face other challenges to RES-E implementation and sustainability. Implementation challenges include an investment climate perceived as risky, and limited access to financial resources [15,16]. Sustainability challenges include inadequate operation and maintenance (O & M) funding [9], or resistance from recipient communities unwilling to accept a novel technology [17].

Literature identifies economic, policy, societal, technological, and environmental factors impacting RES-E implementation. Research also suggests those factors are interactive; exhibiting complex relationships. Interactivity adds to the complexity of RES-E implementation; impacting stakeholders, decisions, or implementation processes across the RES-E deployment landscape [18–20]. Interactivity also increases the difficulty of assessing the impact an individual factor has on RES-E implementation outcomes [21,22].

Only two studies critically review interactions between RES-E implementation factors. Chicco and Mancarella [23] focused on technology, examining interactions between renewable and conventional electricity generation technologies when both types of technologies are employed. The authors found diversifying the generation technologies in combination with energy storage and smart grid capabilities, increased production efficiency and grid resiliency. Edenhofer et al. [24] examine policy interactions, focusing on the role of renewable energy technologies in climate change mitigation, specifically their ability to reduce carbon intensity. The authors suggest policy support is required to overcome market inequalities between RES-E and fossil fuel based electricity. Incentives should be designed to create a long-term investment climate where RES-E is favored over fossil fuel electricity production.

Both studies are limited by a focus on interactions within a single dimension, and the broader impacts of interdependencies between economics, policy, societal, technological or environmental dimensions are not addressed. This paper builds on the previously discussed studies, filling the knowledge gap by first identifying interactions and classifying them into categories. This is followed with a critical review of interactions between RES-E implementation factors within a single, or across multiple dimensions, and then a synthesis of research across all dimensions. The paper is organized with an introduction, followed by the methodology used to select, evaluate, and classify articles included in the review. Political, societal, environmental, and technological interactions are then reviewed. Finally, this paper identifies systemic challenges, knowledge gaps, and future research needs in this field.

2. Methods

2.1. Literature search

A literature search using Web of Science was conducted with the following key words: renewable, energy, and interaction. The search was refined in two ways. The first limited manuscripts to English. To ensure the most current literature was reviewed, manuscripts were also limited to the year 2000 and later. This search returned 554 manuscripts. Of these, 41 were included for review based on the title, abstract, or conclusion/discussion containing the word interaction, or evidence of relationships described in the manuscripts. To verify the results, a second search using Science Direct and the same keywords was performed. This returned 39,174 results. Refining this to the topic “Energy” yielded