Abstracts of 89 Peer-Reviewed Published Journal Articles From 37 Independent Research Groups With Over 210 Different Authors Supporting the Result That Energy for Electricity, Transportation, Building Heating/Cooling, and/or Industry can be Supplied Reliably with 100% or Near-100% Renewable Energy at Different Locations Worldwide

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Impacts of green hydrogen for steel, ammonia, and long-distance transport on the cost of meeting electricity, heat, cold, and hydrogen demand in 145 countries running on 100% wind-water-solar

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A B S T R A C T

As the world moves to clean, renewable energy, questions arise as to how best to produce and use hydrogen. Here, we propose using hydrogen produced only by electrolysis with clean, renewable electricity (green hydrogen). We then test the impact of producing such hydrogen intermittently versus continuously for steel and ammonia manufacturing and long-distance transport via fuel cells on the cost of matching electricity, heat, cold, and hydrogen demand with supply and storage on grids worldwide. An estimated 79, 32, and 91 Tg-H_2/y of green hydrogen are needed in 2050 among 145 countries, for steel, ammonia, and long-distance transport, respectively. Producing and compressing such hydrogen for these processes may consume ~12.1% of the energy needed for end-use sectors in these countries after they transition to 100% wind-water-solar (WWS) in all such sectors. This is less than the energy needed for fossil fuels to power the same processes. Due to the variability of WWS electricity, producing green hydrogen intermittently, rather than continuously, thus with electrolyzer use factors significantly below unity (0.2–0.65), may reduce overall energy costs with 100% WWS. This result is subject to model uncertainties but appears robust. In sum, grid operators should incorporate intermittent green hydrogen production and use in planning.

1. Introduction

As the world transitions from fossil fuels, bioenergy, and uranium to clean, renewable, and safe energy sources to address air pollution, global warming, and energy security, questions arise as to how hydrogen should be produced, what it should be used for, and whether its use can improve grid stability. In this study, hydrogen's source is narrowed to electrolysis, where the electricity originates from wind-water-solar (WWS) electricity (green hydrogen). Green hydrogen's uses are then limited to steel and ammonia manufacturing and long-distance transport. Finally, the impacts of producing green hydrogen intermittently, instead of continuously, on the cost of grid stability are modeled in 145 countries after they have transitioned to 100% WWS all-sector energy economies. Table S2 summarizes the main components of a WWS system: WWS electricity and heat generation; electricity, heat, and cold, storage; hydrogen production, storage, and use; electric machines and appliances; and electricity and heat grids.

Previous studies have examined the potential impacts of emissions, including hydrogen leaks, from producing and using hydrogen for fuel cells, on stratospheric ozone [1]; tropospheric gas pollution and climate [2,3]; tropospheric and stratospheric gas pollution [4]; tropospheric gas and particle pollution and climate [5,6]; and tropospheric and stratospheric ozone, gas, and particle pollution, and climate [7].

With respect to hydrogen production, Jacobson et al. [5] and Colella et al. [6] compared the impacts on pollution and climate-relevant emissions of hydrogen produced by wind-electrolysis (green hydrogen), steam methane reforming (SMR) (gray hydrogen), and coal gasification (brown or black hydrogen). Howarth and Jacobson [8] and Bauer et al. [9] compared the carbon-equivalent emissions of gray versus blue hydrogen (gray hydrogen with carbon capture).

The three applications of green hydrogen treated here are steel and ammonia manufacturing and long-distance transport through fuel cells by aircraft, ship, train, semi-truck, and military vehicle. Green hydrogen may also be used chemically in other industrial processes, but these processes are not treated here. All industrial heat in the present study is provided with electric heaters, such as arc furnaces, induction furnaces, resistance furnaces, dielectric heaters, electron beam heaters, and heat pumps, where all electricity comes from WWS.

Several applications of hydrogen - for heating buildings, powering passenger vehicles, and producing grid electricity - are also not treated here. Hydrogen should not be piped, either on its own or in a mixture with natural gas, to homes for air or water heating [10]. The better alternative is to heat buildings with WWS-powered electric heat pumps. Although using green hydrogen in fuel cells for passenger vehicles is

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Energy system transition pathways to meet the global electricity demand for ambitious climate targets and cost competitiveness

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HIGHLIGHTS

- 9 global transition pathways are analysed for decarbonisation of electricity sector.
- Input-output data of simulation models are remodelled by a cost-optimisation model.
- The least-cost, highly diversified, and business-as-usual pathways are compared.
- Pace, CO_2 costs and energy diversity are found crucial across the scenarios.
- Ambitious paths show competitive costs, ranging between 45.2 and 59.2 €/MWh by 2050.

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ABSTRACT

This study presents a novel energy system modelling approach for the analysis and comparison of global energy transition pathways for the decarbonisation of the electricity sector. The results of the International Energy Agency (IEA), and the Teske/DLR scenarios are each reproduced. Additionally, five new energy transition trajectories, called LUT, are presented. The research examines the feasibility of each scenario across nine major regions in 5-year intervals, from 2015 to 2050, under a uniform modelling environment with identical technical and financial assumptions. The main differences between the energy transition paths are identified across: (1) the average electricity generation costs; (2) energy diversity; (3) system flexibility; (4) energy security; and, (5) transition dynamics. All LUT and Teske/DLR scenarios are transitioned to zero CO_2 emissions and a 100% renewable energy system by 2050 at the latest. Results reveal that the LUT scenarios are the least-cost pathways, while the Teske/DLR scenarios are centred around energy diversity with slightly higher LCOE of around 10–20%. The IEA shares similarities with the Teske/DLR scenarios in terms of energy diversity yet depends on the continued use of fossil fuels with carbon capture and storage, and nuclear power. The IEA scenario based on current governmental policies presents a worst-case situation regarding CO_2 emissions reduction, climate change and overall system costs.

1. Introduction

Global temperature rise and extreme weather events, such as floods, droughts, wildfires and so on, have unceasingly hit new records [1]. If no serious action is taken, yearly mortality rates caused by climate change will be more than that of the COVID-19 pandemic by mid-century [2], while fatalities due to air pollution caused by fossil fuel and unsustainable biomass combustion are in the same order already today [3,4]. The energy system, as one of the main contributors to the climate crisis, accounted for almost 90% of the total carbon dioxide (CO_2) emissions and around 75% of the total greenhouse gas (GHG) emissions in 2018 [5]. This amount is expected to increase if the current situation in the energy system remains unchanged in the decades to come. An investigation into the historical financial performance of energy

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Techno-economic feasibility of hybrid PV/wind/battery/thermal storage trigeneration system: Toward 100% energy independency and green hydrogen production

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ABSTRACT

With the clear adverse impacts of fossil fuel-based energy systems on the climate and environment, ever-growing interest and rapid developments are taking place toward full or nearly full dependence on renewable energies in the next few decades. Estonia is a European country with large demands for electricity and thermal energy for district heating. Considering it as the case study, this work explores the feasibility and full potential of optimally sized photovoltaic (PV), wind, and PV/wind systems, equipped with electric and thermal storage, to fulfill those demands. Given the large excess energy from 100% renewable energy systems for an entire country, this excess is utilized to first meet the district heating demand, and then to produce hydrogen fuel. Using simplified models for PV and wind systems and considering polymer electrolyte membrane (PEM) electrolysis, a genetic optimizer is employed for scanning Estonia for optimal installation sites of the three systems that maximize the fulfillment of the demand and the supply–demand matching while minimizing the cost of energy. The results demonstrate the feasibility of all systems, fully covering the two demands while making a profit, compared to selling the excess produced electricity directly. However, the PV-driven system showed enormous required system capacity and amounts of excess energy with the limited solar resources in Estonia. The wind system showed relatively closer characteristics to the hybrid system but required a higher storage capacity by 75.77%. The hybrid PV/wind-driven system required a total capacity of 194 GW, most of which belong to the wind system. It was also superior concerning the amount (15.05×10^9 tons) and cost (1.42 USD/kg) of the produced green hydrogen. With such full mapping of the installation capacities and techno-economic parameters of the three systems across the country, this study can assist policymakers when planning different country-scale cogeneration systems.

1. Introduction

The need to lessen the threat of climate change has been addressed in the Paris agreement. The suggested efforts include limiting the temperature increase to 1.5 °C by lowering greenhouse gas emissions (United Nations, 2015). Creating climate-sustainable and friendly energy is required since around 80% of the greenhouse gas emissions are emitted from the energy sector, which led the European Energy Union to adopt "A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy" (The European Commission, 2014). Adopting this strategy could aid in achieving the objectives of a green solution to reduce global temperature. The strategy may include the transitions to renewable energy (RE) systems. Solar, wind,

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Planning the deployment of energy storage systems to integrate high shares of renewables: The Spain case study

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ABSTRACT

The intermittent nature of the renewable energy sources with the greater potential, wind and solar, requires dealing with temporary mismatches between demand and supply. The object of this study is to assess the Spanish energy plan from a system perspective regarding the energy storage requirements to meet electricity demand with high penetrations of renewable energy generation. We use a model that builds on existing literature and commercial software and integrates features such as demand response modelling, the correlation between reserve requirements and the technology mix, and hydrogen as an energy vector. This representation is applied to the Spanish electricity system to assess the consistency of the targets of the national energy strategy. Several scenarios of costs, demand and variation of other parameters are simulated to analyse their relative influence on the solution of minimum cost, especially assessing the sensitivity of energy storage capacity. The simulation results show that the Spanish goals for decarbonising the electricity system are based on optimistic assumptions. Also, energy storage will play a more important role than expected, and the use of hydrogen for energy storage is only needed for a 100% penetration of renewable energies.

1. Introduction

Mitigation measures are mandatory to achieve the Paris agreement scenario [1], and the decarbonisation of the power sector is a crucial element to stay under the 2 °C objective scenario [2]. Power systems will be based on variable Renewable Energy Sources (RES), especially wind and solar technologies [3]. However, due to their stochastic nature, these technologies face a major problem, the unavailability to constantly supply electricity [4]. Thus, future power systems will require storage technologies to balance and compensate RES generation [5–7]. Moreover, emissions-free power systems will have to cope with current demand and the electrification of transport, building energy needs, etc. [8], increasing the requirements of RES capacity, energy storage and other balancing resources.

Countries are releasing strategic plans with RES and energy storage objectives to achieve decarbonised power systems. However, these tend to lack precision, for example, calculation of capacities required of energy storage, compatible strategies such as demand response or specificities about storage technologies and sector coupling. As mentioned above, there is a need for energy storage to achieve full decarbonisation of electricity systems, but storage technologies are still capital intensive, not mature, and have a high level of uncertainty concerning their technical and cost development. This has led to strategic plans with lack of precision regarding the needed investment and optimal operations of energy storage technologies [9]. However, correctly planning the storage needs and their deployment is crucial to benefit from the least-cost path to reach the decarbonisation targets with a reliable power system.

Modelling studies have long served as a basis for planning and decision-making. In that regard, there is a line of research regarding 100% RES energy modelling to help decision makers to address the needs of fully decarbonised energy systems [9]. Early studies date back to the start of the century [10], but it is only in recent years that the attention to them has increased exponentially [9]. Several authors have provided world-scale studies to evaluate country by country the main features of systems with high integration of RES [11,12]. Other researchers have studied regional pathways [13,14] or country scale models [15,16]. Nevertheless, there is a need to continue studying the impact of the evolution of the technology mix and the flexibility requirements that the energy transition entails [9].

Energy storage is critical to reducing the system's need for backup and curtailment [17]. [7] analyse how different types of storage are considered in energy system modelling. They conclude that dispatching different storage technologies depends on the other available

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Synergies of electrical and sectoral integration: Analysing geographical multi-node scenarios with sector coupling variations for a transition towards a fully renewables-based energy system

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ABSTRACT

The cost-optimal pathway for moving from the current fossil-fuel based energy system to 100% renewables is still an open question. This work presents the first study that analyses the transition towards a 100% renewable energy system under different spatial resolutions (1-node, 6-nodes electrically isolated and interconnected) and various coupling configurations for the power, heat, transport and desalination sectors. With the LUT Energy System Transition Model for the case of Chile, 12 scenarios were investigated in an hourly resolution and considering more than one hundred energy-related technologies. The results show that: (1) 1-node systems deliver too simplistic results for key metrics; (2) power sector simulations can lead to a strongly distorted resources allocation compared to scenarios that include other sectors; (3) a multi-node model better reflects transmission bottlenecks and local resources, and; (4) the lowest-cost solution is reached when power transmission lines are considered. Thus, it is concluded that a cost-optimal, balanced, and realistic solution to reach a fully defossilised energy system is transitioning towards a multi-node, interconnected, and fully sector-coupled energy system. This can be called, in short, the 'Power-to-X economy', which in the case of Chile would more accurately be a 'Solar-to-X economy', given the high solar share found in the simulations.

1. Introduction

The most feasible, sustainable and low-cost option to achieve the Paris Agreement target is transitioning towards a fully renewable-based energy system across all sectors [1–3]. This would be based on direct and indirect electrification across all energy-demanding sectors [4–6]. Moreover, such a transition has been reported to be an essential socio-economic contributor to job creation at global and local levels [7,8]. However, understanding the most cost-optimal pathway for going from the current fossil fuel-based energy system to an entire system based on 100% renewable energy (RE) by 2050 is still an open question [9]. This is seen to be even more challenging in developing countries [10].

Although the design of 100% RE systems has been studied at

Abbreviations: (A-CAES), Adiabatic compressed air energy storage; (BEV), Battery electric vehicle; (CO_2), Carbon dioxide; (CDR), carbon dioxide removal; (DACCS), direct air captured carbon storage; (DH), District heating; (FT), Fischer-Tropsch; (GW), Gigawatt; (GHG), Greenhouse gas; (LCOE), Levelised cost of electricity; (LNG), Liquefied natural gas; (LT), Low temperature; (LUT-ESTM), LUT Energy System Transition Model; (MDV), Medium duty vehicle; (MT), Medium temperature; (MWh), Megawatt-hour; (PV), Photovoltaics; (P), Power; (PH), Power and heat; (PHT), Power, heat and transport; (PHTD), Power, heat, transport and desalination; (PtH), Power-to-heat; (PtX), Power-to-X; (PHES), Pumped hydro energy storage; (RE), Renewable energy; (SNG), Synthetic natural gas; (TTW), Tank-to-wheel; (TW), Terawatt; (TWh), Terawatt-hour; (TES), Thermal energy storage; (€), Euro.

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H_2 contribution to power grid stability in high renewable penetration scenarios

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HIGHLIGHTS

- The synergy of Li-Ion batteries and hydrogen is evaluated to ensure grid balance.
- Hydrogen integration has been evaluated in the path to 100% renewable energy.
- The optimum solution is a tradeoff between renewable share and system cost.
- A fully renewable system would cost \$0.42/kWh with a 30% hydrogen contribution.
- Hydrogen power-to-power system is strongly limited by high cost.

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ABSTRACT

The paper proposes the analysis of four different scenarios of renewables penetration (40%, 60%, 80%, and 100%) with the most affordable generators: photovoltaic panels and wind turbines. The synergy of two storage technologies, such as Li-Ion batteries and the hydrogen power-to-power solution (electrolyzer, H_2 tank, and fuel cells), is evaluated to ensure the balance of the power-grid. The paper discusses the numerical Trnsys-based modeling of the smart grid. A detailed performance evaluation of each component, according to operational maps provided by manufacturers, has been performed to meet an electrical load (10 MW peak - 54 GW h annual). The results of the analysis show the crucial role of the H_2 system in the goal of achieving a higher renewable fraction, mainly due to the possibility of seasonal storage without the self-discharge limitation of batteries. In the 100% renewable solution the contribution of H_2 is equal to 30% of the electric load.

Introduction

The future of power generation is related to the energy transition from fossil-based systems to the renewable energy sources. To facilitate this transition, smart grids have proven to be the best way to increase the contribution of renewables as opposed to replacing and strengthening traditional grids [1]. Non-programmable generation could affect grid stability and capability to meet nighttime load [2], however, the inclusion of energy storage system is a promising option to increase reliability of power supply solving problems of unstable and unpredictable renewables sources [3]. The hydrogen system is an emerging alternative to batteries as storage solution, especially with large timescale (in order of weeks or months),

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Smart strategies for the penetration of 100% renewable energy for the Ecuadorian Amazon region by 2050

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ABSTRACT

This research presents a 100% renewable system configured based on its real potential and use of renewable energies for the Ecuadorian Amazon, considered one of the places with the greatest diversity of native plant species on the planet. The transition processes that are born from the central state seek to take a radical turn in the electricity sector but there is still no defined roadmap, this is where this research will allow it to be an important reference for its long-term transformation. The current system is based on fossil fuels and in this study an energy transition process is planned with the support of the EnergyPLAN tool that puts into practice the concept of intelligent energy, progressively and systematically achieving 100% renewable energy for 2050. Finally, after analyzing the results, it is concluded that the energy mix for 2050 can consider 36.47% hydro, 33.04% solar photovoltaic, 29.73% wind energy and other technologies to a lesser extent with 0.74%. Surpluses can be injected into the interconnection sites with Colombia and Peru, also achieving economic income to preserve and expand the infrastructure of the electricity sector. Decision makers can consider this study as a reference before committing economic resources and carrying out modern energy planning.

1. Introduction

Since the eighties of the last century, more oil has been consumed in the world than is discovered. The ratio is approximately four to one. Although the percentage that oil represents of the total primary energy consumption in the world has been falling in recent years (in 1973 it represented 46%, while now it is approximately 35%) (Wachtmeister et al., 2018), the demand for this energy resource has not stopped increasing (85 million barrels per day, currently, with a growth of 1% per year) (Baumeister and Kilian, 2016). The economic emergence of countries such as China or India has made oil an even more desirable source of energy worldwide, and the regions from which the known proven reserves are extracted squeeze their wells and seek new deposits to cushion the decline of their proven reserves current (Lund, 2010). According to various international organizations such as the International Energy Agency (IEA) (World Energy Investment, 2021, 2021, 2021) or the United States Department of Energy (USDE) (Department of Energy, 2022), currently proven world reserves are about 165,000 million tons. The most recent predictions reduce the expected production for the next few years, since at most it will reach 106 million barrels per day in 2030 (Stytsenko et al., 2008). According to these data, if humanity consumes oil at the same rate as it has done so far, oil reserves are expected to run out in 40–50 years (Elmaghraby et al., 1981).

In this context of growing demand for oil, we are very close to reaching, if we have not already surpassed it, as some experts and world institutions point out, the point at which maximum production is achieved and half of the initially existing oil is reached, known as peak oil or zenith oil. Most governments know that this peak oil exists, the global energy strategy has not been able to change the trend and provide real solutions applicable in the medium term (Li et al., 2022). Countries whose economy depends on a high percentage of oil imports will have to introduce large-scale structural changes in their energy system if they want to project their current level of growth into a more robust one in the long term: saving and efficiency, renewable energies and diversification are concepts that will characterize the future global energy system (Thellufsen et al., 2020). The search for and innovation in terms of new energy sources will be other factors that will contribute to drawing a new world energy scenario.

In Ecuador, it is a clear example of oil affection, specifically foreign multinationals exploited oil wells without severe plans to protect the ecosystem and the consequences were diverse, from the destruction of vegetation to the invasion of territories and homes of uncontacted indigenous peoples and nationalities (Finer et al., 2010). The center of

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Research Papers

Towards 100% renewable energy systems: The role of hydrogen and batteries

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A B S T R A C T

New challenges arise for the accurate modelling of energy systems with a high share of renewable energy. In this context, energy storage technologies become key elements to manage fluctuations in renewable energy sources and electricity demand. The aim of this work is to investigate the role of batteries and hydrogen storage in achieving a 100% renewable energy system. First, the impact of time series clustering on the multi-year planning of energy systems that rely heavily on energy storage is assessed. The results show good accuracy, even for a small number of representative days, which is necessary to limit the computational burden of the optimisation problem. Then, different configurations of carbon-free energy systems are considered by varying the energy storage solution: only-battery, only-hydrogen, and hybrid scenarios. An island energy system based on photovoltaics and floating offshore wind turbines is used as a demonstrative case study. It is shown that the cost of the only-battery configuration is 155% higher than the cost of the hydrogen-based scenarios. The reason is that the long-term hydrogen-based storage, despite its low round-trip efficiency, avoids costly oversizing of batteries and wind turbines throughout the analysed period. In the selected case study, hydrogen storage reduces the total rated power of the wind farm by about 5 times compared to the only-battery system. Hydrogen-based solutions are therefore crucial in 100% renewable energy systems to achieve energy self-sufficiency in a cost-effective way.

1. Introduction

In recent years, there has been growing interest in developing sustainable energy systems based on renewable energy sources (RESs). The deployment of RESs at a large scale is the first step in the transition to a low-carbon economy. However, the fluctuating behaviour of variable RESs, e.g., wind and solar, leads to new challenges in terms of electric grid management and energy storage. The installed capacity of electrical energy storage (EES) systems is thus expected to increase significantly in the coming years. Energy storage solutions can be of different types: mechanical, electrochemical, chemical, electrical and thermal [1,2]. Batteries offer high efficiency and fast response time [3], making them ideal candidates when small size and short-term energy storage is needed. Hydrogen is also expected to become essential as a storage solution in RES-based scenarios due to its long-term storage capability and high energy density [4]. Hydrogen can be generated in a sustainable way through water electrolysis powered by renewable energy [5]. Once hydrogen is produced, it can be stored and later reconverted into electricity according to the so-called power-to-power (PtP) route. Moreover, and differently from a closed battery (pure role of electrical storage), hydrogen can assume other roles: as feedstock for production of gaseous and liquid synthetic chemicals via dedicated power-to-X (PtX) routes in

Abbreviations: BATT, Battery; CAPEX, Capital Expenditures; DG, Diesel Generator; EES, Electrical Energy Storage; ELY, Electrolyser; FC, Fuel Cell; HRES, Hybrid Renewable Energy System; HT, Hydrogen Tank; HYB, Hybrid; LP, Linear Programming; MILP, Mixed Integer Linear Programming; NPC, Net Present Cost; OB, Only-Battery; OF, Objective Function; OH, Only-Hydrogen; OPEX, Operating Expenditures; PEM, Proton-Exchange Membrane; PtP, Power-to-Power; PtX, Power-to-X; PV, Photovoltaic; RD, Representative Day; RES, Renewable Energy Source; TRAD, Traditional; WT, Wind Turbine.

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Review

Highly renewable energy systems in Africa: Rationale, research, and recommendations

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SUMMARY

This review paper, the first to examine Africa's state of the art fully renewable energy system analyses, assesses the status and findings of 100% renewable energy system analyses for Africa published in scientific journals. In total, 54 articles published since 2000 have been identified and analyzed. Most of these studies are relatively new and focus on the power sector, while less attention is given to other energy sectors. Despite being projected to account for a quarter of world population by 2050, Africa is the least researched region for 100% renewable energy systems in the world. Notably, the geographical scope of 100% renewable energy research in Africa is limited; Morocco and Nigeria are the most researched countries, but France's overseas department of La Réunion receives the same attention, which reinforces the point of lack of interest or focus of the research community on the African continent. The literature review further documents significant gaps in fully renewable energy system research for Africa, including low resolution in sector coverage, time, space, and applied technology diversity. Despite Africa being the continent suffering from the lowest rates of electricity access, there is no single energy system model that can coherently model the transition of on-grid and off-grid solutions in a comprehensive energy system transition.

INTRODUCTION

Transitioning to renewable energy (RE) for all purposes is at the core of the solutions to climate change.[1] Limiting global warming will require significant transitions in the energy system, a substantial reduction in fossil fuel use, improved energy efficiency, and direct and indirect electrification of hard-to-abate energy demands in the industry and transport sectors.[1,2]

For the African continent, with its currently low levels of access to electricity and other modern forms of energy, transitioning to renewables may not appear to be a priority, given that the logical focus is on growing existing systems to provide increased access to a growing population. Yet, in scientific and gray literature, various rationales have been proposed on why planning for highly RE systems is increasingly an interesting and attractive option for the African continent. We have often referred to these as 100% RE systems to simplify the concept. However, for the peer-reviewed articles included in this review, a minimum threshold of 95% applies; thus, the term highly RE systems would be equally applicable. This criterion was applied to include near-100% RE system analyses and ensure all features of 100% RE systems and fossil energy-free solution structures. We start this paper by outlining these four rationales below: (1) the cost-competitive rationale, (2) the

CONTEXT & SCALE

This review paper assesses the status and findings of 100% renewable energy (RE) system analyses for Africa published in scientific journals. The 100% RE topic is rarely researched with regard to Africa; only 54 peer-reviewed articles exist for the entire continent, which is about 7% of the global total (750 articles) while reflecting almost a quarter of the world population by 2050. As a comparison, more 100% RE system analyses exist for the 5.9 million inhabitants of Denmark than for the 1.34 billion inhabitants of Africa. The literature review documents significant gaps in Africa's fully RE system research.

The review shows that studies on RE transitions have mainly focused on the Global North. Comparative studies on fully RE transition and supportive RE policies for the Global South, especially for Africa, are rare. Studies on 100% RE for Africa can be characterized by low resolution in sector coverage, time, space, and applied technology diversity. The geographical scope of 100% RE research in Africa is limited; Morocco, Nigeria, and La Réunion Island are the most researched countries; however, La Réunion is politically part of Europe. Africa is the world region suffering from the lowest electricity access. However, no single energy system

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RESEARCH ARTICLE

Evaluation of Australia's Generation-Storage Requirements in a Fully Renewable Grid With Intermittent and Flexible Generation

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ABSTRACT Energy storage is crucial for grids with high renewable penetration to ensure reliable power supply during low renewable generation periods and address the intermittency associated with weather-dependent resources. However, sizing grid-scale storage presents challenges due to its interdependence on renewable generation and load profiles. This paper investigates the minimization of storage requirements for Australian grids as a case study in a fully renewable scenario and examines how inflexible generation (such as solar and wind) and flexible generation (such as hydro) affect the capacity requirements. Investigating the role of generation technology in sizing storage is paramount for a fully renewable grid and, therefore, sets this work apart from previous studies that primarily focused on grid capacity expansion planning. Moreover, unlike studies that rely on simulated profiles, our study distinguishes itself by utilizing high-resolution real-world generation data from existing generators. We extend our analysis to the economic trade-off between investing in increased storage versus intentional excess renewable generation. Subsequently, the optimum generation-storage requirement is analyzed, and regional requirements with and without interconnectors are estimated. Finally, we analyze storage annual utilization and present a sensitivity analysis to variations in technology costs. The quantitative results suggest that optimal storage size is contingent upon the renewable mix, and while solar generation is cost-competitive, higher contributions from wind generation and strategic dispatch of hydro generation are required to achieve an optimum generation-storage solution. We show that storage with a power capacity slightly lower than the mean annual demand with a duration of one day is required for Australia's National Electricity Market (NEM); in absolute terms, there exists a storage requirement of 18.5—21.5 GW and 400—770 GWh for a fully renewable grid. These findings underscore the importance of carefully balancing the renewable mix to achieve an efficient and cost-effective grid. Based on estimated future costs for long-duration storage and generation technology, the optimum generation-storage solution will translate into an investment of approximately 9.8% of the country's Gross Domestic Product (GDP)—this investment is achievable when amortized over 10–15 years for the transition to a near-100% renewable grid.

INDEX TERMS 100% renewable electricity grid, Australian energy transition, energy economics, long-duration energy storage, storage optimization.

NOMENCLATURE

Parameters

Δt	Sampling interval, $\Delta t = 1/12$ h.
η_c	Charging efficiency of the energy storage.
η_d	Discharging efficiency of the energy storage.
max	Superscript identifying maximum value over analyzed duration.
min	Superscript identifying minimum value over analyzed duration.
C^e_{ES}	Cost per unit of rated storage energy capacity.

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PAPER

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Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries†

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Global warming, air pollution, and energy insecurity are three of the greatest problems facing humanity. Roadmaps are developed and grid analyses are performed here for 145 countries to address these problems. The roadmaps call for a 100% transition of all-purpose business-as-usual (BAU) energy to wind-water-solar (WWS) energy, efficiency, and storage, ideally by 2035, but by no later than 2050, with at least 80% by 2030. Grid stability analyses find that the countries, grouped into 24 regions, can exactly match demand with 100% WWS supply and storage, from 2050–2052. Worldwide, WWS reduces end-use energy by 56.4%, private annual energy costs by 62.7% (from \$17.8 to \$6.6 trillion per year), and social (private plus health plus climate) annual energy costs by 92.0% (from \$83.2 to \$6.6 trillion per year) at a present-value cost of ∼\$61.5 trillion. The mean payback times of the capital cost due to energy- and social-cost savings are 5.5 and 0.8 years, respectively. WWS is estimated to create 28.4 million more long-term, full-time jobs than lost worldwide and may need only ∼0.17% and ∼0.36% of world land for new footprint and spacing, respectively. Thus, WWS requires less energy, costs less, and creates more jobs than BAU. Sensitivity test indicate the following. Increasing district heating and cooling may reduce costs by allowing flexible loads to replace inflexible loads, thereby replacing electricity storage and overgeneration with low-cost heat storage. A battery cost that is 50% higher than in the base case increases mean overall energy costs by only 3.2 (0.03–14.5)%. Almost all regions need fewer hours of load shifting than assumed in the base case, suggesting that actual load shifting may be easier than assumed. Increasing the use of electricity for hydrogen fuel-cell-electric vehicles instead of for battery-electric vehicles increases overall cost in most regions tested, due to the greater efficiency of battery-electric vehicles, but decreases overall cost in some regions by improving grid stability. Finally, shifting battery vehicle charging from day-night to mostly day charging reduces cost in the regions tested; shifting to mostly night charging increases cost. Ninety-five percent of the technologies needed to implement the plans proposed are already commercial.

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Broader context

The world is undergoing a transition to clean, renewable energy to reduce air pollution, global warming, and energy insecurity. To minimize damage, all energy should ideally be transitioned by 2035. Whether this occurs will depend substantially on social and political factors. One concern is that a transition to intermittent wind and solar will cause blackouts. To analyze this issue, we examine the ability of 145 countries grouped into 24 regions to avoid blackouts under realistic weather conditions that affect both energy demand and supply, when energy for all purposes originates from 100% clean, renewable (zero air pollution and zero carbon) Wind-Water-Solar (WWS) and storage. Three-year (2050–52) grid stability analyses for all regions indicate that transitioning to WWS can keep the grid stable at low-cost, everywhere. Batteries are the main electricity storage option in most regions. No batteries with more than four hours of storage are needed. Instead, long-duration storage is obtained by concatenating batteries with 4 hour storage. The new land footprint and spacing areas required for WWS systems are small relative to the land covered by the fossil fuel industry. The transition may create millions more long-term, full-time jobs than lost and will eliminate carbon and air pollution from energy.

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1. Introduction

Global warming, air pollution, and energy insecurity remain three of the greatest problems facing the world. The Earth's

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Energy transition in megacities towards 100% renewable energy: A case for Delhi

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A B S T R A C T

The transition away from fossil fuels towards renewable energy is critical in preventing perilous climate change, and cities around the world have a significant role in enabling this transition. Cities are innately centres of human, economic and intellectual capital, also contributing to the growing energy demand around the world. This research is a first of its kind to explore the technical feasibility and economic viability of 100% renewable energy systems including power, heat, transport and desalination sectors for a global megacity like Delhi within the North Indian grid region. It presents a technology-rich, multi-sectoral, multi-regional and cost-optimal energy transition pathway for Delhi, which is a hub within the regional energy system. The results of this research indicate that a megacity such as Delhi can benefit and drive a regional energy transition, with reduction in primary energy of over 40%, reduction in energy costs by over 25%, reduction in greenhouse gas emissions, air pollution and associated health costs. While creating more than three times the number of direct energy jobs as of today across North India and Delhi. With the case of Delhi within the North Indian grid, this research provides snapshots of the current and future energy landscapes and discusses several aspects of an energy transition pathway that could lead to an affordable, efficient, sustainable and secure energy future for megacities around the world.

1. Introduction

Global greenhouse gas (GHG) emissions must be reduced by an additional 25% along with existing commitments for 2030, to get on track towards the 1.5 °C temperature goal of the Paris Agreement [1]. In order to enable this, cities around the world have a key role in shaping energy transitions. The city, one of the world's biggest phenomena of the 21st century has evolved greatly over the centuries, particularly in terms of its size, form, structure and composition, while largely maintaining its importance in local, regional and increasingly in global development [2]. However, the definition of a city varies around the world and the United Nations (UN) formulated a consensus that a city can be conceptualised in terms of its urban extent or the degree of urbanisation [2]. This classifies a high-density cluster or urban center as having a density of at least 1500 inhabitants per km^2 and a minimum population of 50,000 [2]. The city as a unit of analysis is critical to overcoming future challenges and for better positioning of cities as engines of sustainable development.

Cities contribute massively to the growing energy demand with two-thirds of global energy consumption, and by extension are responsible for 70% of global GHG emissions [3]. Moreover, cities around the world are home to 55% of the global population, which is expected to increase to nearly two-thirds by 2050 [4]. This implies cities will be central to drive energy transitions in regions and countries around the world. Some cities are making progress, as reported by Carbon Disclosure Project (CDP) that 148 cities had reported a 1.5 °C aligned target by the end of 2020 [5]. While most of these targets were reported by North American and European cities along with a few others, a majority of cities and particularly megacities around the world are yet to devise long-term climate targets [6]. According to the UN [3], urban agglomerations having over 10 million inhabitants are counted as megacities. When it comes to cutting emissions, megacities around the world will have to lead with science-based climate targets including energy pathways for reducing GHG emissions to net zero by 2050 [7,8]. Most of these megacities are from developing regions, with a majority in China and India. In addition, India is set to have seven megacities by 2030 with Delhi set to be the most populous city in the world with over 37 million by 2028, overtaking Tokyo [4].

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100% renewable energy in Japan

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ABSTRACT

Low-cost solar photovoltaics and wind offer a reliable and affordable pathway to deep decarbonization of energy, which accounts for three quarters of global emissions. However, large-scale deployment of solar photovoltaics and wind requires space and may be challenging for countries with dense population and high per capita energy consumption. This study investigates the future role of renewable energy in Japan as a case study. A 40-year hourly energy balance model is presented of a hypothetical 100% renewable Japanese electricity system using representative demand data and historical meteorological data. Pumped hydro energy storage, high voltage interconnection and dispatchable capacity (existing hydro and biomass and hydrogen energy produced from curtailed electricity) are included to balance variable generation and demand. Differential evolution is used to find the least-cost solution under various constraints. This study shows that Japan has 14 times more solar and offshore wind resources than needed to supply 100% renewable electricity and vast capacity for off-river pumped hydro energy storage. Assuming significant cost reductions of solar photovoltaics and offshore wind towards global norms in the coming decades driven by large-scale deployment locally and global convergence of renewable generation costs, the levelized cost of electricity is found to be US$86/Megawatt-hour for a solar-dominated system, and US$110/Megawatt-hour for a wind-dominated system. These costs can be compared with 2020 average system prices on the spot market in Japan of US$102/Megawatt-hour. Cost of balancing 100% renewable electricity in Japan ranges between US$20–27/Megawatt-hour for a range of scenarios. In summary, Japan can be self-sufficient for electricity supply at competitive costs, provided that the barriers to the mass deployment of solar photovoltaics and offshore wind in Japan are overcome.

1. Introduction

Following the recently held 2021 United Nations Climate Change Conference (COP26), 151 countries have submitted new climate plans targeting emissions in 2030 [1]. For the longer term, over 100 countries have committed to carbon neutrality by 2050–2060, including major economies such as China, the United States (US), Japan and the Europe Union [2]. Globally, the cost of solar photovoltaics (PV) and wind energy is falling and, in many places, is cheaper than the cost of electricity from new-build coal and gas power stations [3]. Solar PV and wind now account for three quarters of global net capacity additions due to their low and falling prices [4].

Low-cost solar PV and wind, when balanced by storage, transmission, and demand management, offer a reliable and affordable pathway to deep cut in emissions that is enabled by the switch to renewable energy for power generation and renewable electrification of transport, heat, and industry [4]. This pathway can be readily applied to many countries with good solar and wind resources and sufficient available land area for the deployment of solar and wind farms, such as China, the US, and Australia. However, it could be more challenging for countries such as Japan, South Korea and Germany, which have relatively small land area, dense population, and high per capita energy consumption. These countries also lack sufficient hydro resources to supply majority of their energy needs, unlike countries with low population density such as New Zealand and Iceland. In this paper the future role of renewable energy, in particular solar and wind, in these small, developed and densely populated countries, is examined from both technical and economical perspectives. This study focuses on Japan as an example.

Japan is the fifth largest greenhouse gas (GHG) emitter in the world, with low energy self-sufficiency due to the lack of conventional energy resources (coal, oil, gas). Japan currently generates 21% of its electricity from renewables, with the balance comprising nuclear (7%), fossil fuels (70%) and other (2%) [5]. The decision of the Japanese Government to commit to net-zero emissions in 2050 [6] means that large-scale decarbonization of energy needs to take place in the following

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Zero air pollution and zero carbon from all energy at low cost and without blackouts in variable weather throughout the U.S. with 100% wind-water-solar and storage

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ABSTRACT

This study analyzes 2050–2051 grid stability in the 50 U S. states and District of Columbia after their all-sector (electricity, transportation, buildings, industry) energy is transitioned to 100% clean, renewable Wind-Water-Solar (WWS) electricity and heat plus storage and demand response (thus to zero air pollution and zero carbon). Grid stability is analyzed in five regions; six isolated states (Texas, California, Florida, New York, Alaska, Hawaii); Texas interconnected with the Midwest, and the contiguous U.S. No blackouts occur, including during summer in California or winter in Texas. No batteries with over 4-h storage are needed. Concatenating 4-h batteries provides long-duration storage. Whereas transitioning more than doubles electricity use, it reduces total end-use energy demand by ~57% versus business-*as*-usual (BAU), contributing to the 63 (43–79)% and 86 (77–90)% lower annual private and social (private + health + climate) energy costs, respectively, than BAU. Costs per unit energy in California, New York, and Texas are 11%, 21%, and 27% lower, respectively, and in Florida are 1.5% higher, when these states are interconnected regionally rather than islanded. Transitioning may create ~4.7 million more permanent jobs than lost and requires only ~0.29% and 0.55% of new U.S. land for footprint and spacing, respectively, less than the 1.3% occupied by the fossil industry today.

1. Introduction

The United States is currently undergoing a slow but consistent transition to clean, renewable energy. We define clean, renewable energy as energy that is both clean (emits zero health- and climate-affecting air pollutants when consumed) and renewable (has a source that continuously replenishes the energy). We call energy sources that meet these criteria Wind-Water-Solar (WWS) sources. WWS electricity-generating technologies include onshore and offshore wind turbines (Wind); tidal turbines, wave devices, geothermal electric power plants, and hydroelectric power plants (Water); and rooftop/utility solar photovoltaics (PV) and concentrated solar power (CSP) plants (Solar) (Table 1). WWS heat-generating technologies include solar thermal and geothermal heat plants. WWS electricity must be transported by alternating current (AC), high-voltage AC (HVAC), and high-voltage direct current (HVDC) transmission lines and AC distribution lines (Table 1). WWS energy must also be stored in either electricity, heat, cold, or hydrogen storage media (Table 1). Finally, a transition to WWS requires equipment for transportation, industry, and buildings that runs on electricity. Such equipment includes electric and hydrogen fuel cell vehicles, heat pumps, induction cooktops, arc furnaces, resistance furnaces, lawn mowers, leaf blowers, chainsaws, and more (Table 1).

For this study, we consider only WWS energy since we believe that WWS technologies result in greater simultaneous reductions in air pollution, climate damage, and energy insecurity than do non-WWS technologies. We do not include fossil energy, bioenergy, non-hydrogen synthetic fuels, blue hydrogen, carbon capture, direct air capture, or nuclear energy, since each may result in a greater risk of air pollution, climate damage, and/or energy insecurity. The only hydrogen considered is green hydrogen (from WWS electricity). If we can solve all three problems at reasonable cost with WWS alone, we will not need miracle or controversial technologies to help.

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ORIGINAL PAPER

Decarbonization of EU energy sector: techno-feasibility analysis of 100% renewables by 2050 in Cyprus

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Abstract

Cyprus continues to be one of the European Union's most energy import-dependent countries. It is of worthy note that Cyprus is also the only European Union member state whose electricity grid is not connected to the European power network, as it uses an independent network that relies on local production. The high cost of electricity has been identified as a top problem, and officials on the island are looking at several ways to lower electricity rates. Increasing the amount of renewable energy is one of the main options being looked at. Furthermore, in a bid to meet the European Union target of 40% renewable energy electricity generation, Cyprus needs to fully utilize the vast renewable energy potential in the region. In this study, the integration of dominant renewable energy sources (solar, wind, and concentrated solar power) to the thermal power run grid system is simulated. Also, a 100% renewable energy electricity generation for 2050 is also modelled. The analysis is done, for a projected 8.3TWh/year of electricity demand, in the ENERGYPLAN simulation environment. The deterministic factors considered in this study are the power production and critical excess electricity production. Eight (8) case scenarios were developed in this study for comparative discourse of most feasible electricity generation to cut down on carbon dioxide emission in Cyprus. The optimized analysis reveals that the best case scenario for electricity generation for 2050 is Photovoltaic system integrated with the oil powered plants. This system (Photovoltaic/Oil) would generate 1.68TWh/year of renewable energy electricity. For 100% renewable energy electricity generation, the most feasible option is the Photovoltaic/Wind/storage system. This system would have an installed 4000 MW PV capacity, 7500 MW wind capacity and 30GWh storage capacity. This study gains significance as the results will give valuable technical and economic parameters that can inform policy changes in the region.

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Techno-economic feasibility of thermal storage systems for the transition to 100% renewable grids

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ABSTRACT

Batteries are often used to overcome the intermittency of renewable energy resources. However, Li-ion batteries are associated with tremendous metal depletion, environmental impact, and human health hazards. Thermal energy storage systems are often disregarded in large-scale plans for direct production of electricity due to the losses encountered in the conversion process. Using Jordan as a case study, six different systems were evaluated, namely Photovoltaic (PV)-thermal storage, PV-wind-thermal storage, PV-concentrated solar power (CSP)-thermal storage, PV-CSP-wind-thermal storage, PV-CSP-Li-ion battery, and PV-CSP-wind-Li-ion battery. Different techno-economic parameters were considered to scan for the installation sites of highest demand-supply matching and lowest levelized cost of electricity. The results showed that when thermal storage is adopted, incorporating wind turbines with the solar system decreases the total installation capacity by about 35%, even though larger thermal storage is required. The optimal configurations of PV-CSP-wind-thermal storage and PV-CSP-wind-battery systems have storage capacities of 0.340 TWh_{th} and 0.109 TWh_e, respectively. This work revealed that the integration of thermal storage to renewable power generation systems in Jordan is not only feasible and can cover 100% of the energy requirements at all times, but also can offset the huge need for the more common but perilous alternative (Li-ion batteries).

1. Introduction

The need for clean and carbon-free power systems is increasing, especially in countries such as Jordan, which lack conventional fossil fuel resources and suffer from pollutant emissions. Additionally, the Paris Agreement and Kyoto protocol have forced governments and decision-makers to keep the world temperature increase below 2.0 °C [1]. This regulation can be facilitated by using renewable energy resources to match 100% of the energy demand while keeping the carbon print at the lowest. Consequently, alternative resources for power generation, as well as new and innovative ways of matching the power demand for large-scale applications, are required. Such actions are also required to help mitigate not only climate change but environmental hazards as well. Renewables considered such as PV, wind turbines, tidal waves energy, and biofuels can be considered as alternatives to fossil fuels, where large power consumption is required, such as the energy demand for countries [2–4], cities [5,6], rural areas [7], university campuses [8], and large facilities [9–11].

Photovoltaic (PV) panels and wind turbines are viable solutions to generate electrical energy on large scales, as in entire countries. However, PV and wind turbines suffer from intermittency and geographical limitations due to the short range of solar radiation availability and wind effective speed [12]. A combination of PV, wind turbines, and energy storage systems (ESS), i.e., PV/wind/ESS, is used to mitigate the intermittency and to decrease the mismatch between the demand and energy supplied [13,14]. For example, Camargo et al. [15] optimized the integration of PV/wind/ESS to cover the base load demand of Chile while considering the weather conditions. Their results showed high potential in renewable energy generation and storage.

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Decarbonization of the Galapagos Islands. Proposal to transform the energy system into 100% renewable by 2050

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A B S T R A C T

This research presents a completely decarbonized system structured with renewable energies for the fragile ecosystem of the Galapagos Islands of Ecuador, with a horizon to the year 2050. The transition process begins with clear legal actions and allocating economic resources that clearly promote a change in the energy matrix and the transition would be achieved until the year 2050. The Galapagos Islands are the second largest marine reserve on the planet, declared a World Heritage Site in 1978 for UNESCO. The archipelago, a beautiful ecological attraction, has tourism as its main economic source. The biggest problem is in the supply of energy that mainly comes from fossil fuels, in addition to that, the smell of fuel in several places is out of tune with the harmonious nature and its species. The efforts began to be noticed when in the Archipelago the new implementations of renewable energy began to become a reality with the purpose of stopping using fossil fuels. In this sense, there is the potential to take advantage of the resources available in specific sites, especially the photovoltaic and wind solar considered in the National Plan All a Life. The change in the productive matrix from the national level also implies a change in demand, including at the transportation level with the use of electric vehicles and the use of electric stoves in homes. The purpose is that energy services in the Galapagos Islands progressively increase, on the one hand, replacing fossil fuels and on the other, supplying the growing demand with a view to 2050, taking advantage of renewable energies until reaching 100%.

1. Introduction

Reaching Goal 7 for Sustainable Development (SDG 7) means guaranteeing access to energy in an affordable, reliable, sustainable and modern [1]. An adequate energy supply is a latent need that involves millions of people around the world and most of them have many difficulties to develop economically [2,3]. Historically, fuels have been an important source for the well-being and development of different countries, however it has also contributed with negative consequences, including the increase in the climate on earth [4]. Furthermore, the uses bring with them growing problems of an environmental nature, such as plastic, which, being a derivative of oil, has caused disastrous problems in marine species [5]. These fuels from the so-called Industrial Revolution, acquired prominence in the incipient industrial development, establishing a new economic order through the use of coal. Starting in 1913, with the invention of the oil-derived combustion engine, established a monopoly for obtaining energy used in transportation [6].

Industrialization improved the processes at the beginning of the 21st century with the purpose of exploiting fossil fuels en masse, which put the international community in check [7]. However, due to the high levels of exploitation of fossil fuels, countries experience substantial reductions in their reserves, especially oil, experiencing global climate change that includes fuel shortage problems [8]. Examples of this type are lived in Latin America in countries such as Venezuela [9,10], Bolivia [11], Chile [12], Ecuador [13], Brazil [14]. The common denominator of the countries is that the oil fields are being depleted at a rate never seen before and puts future development at risk [15,16]. The transnational companies are seeking, as possible, concessions with government entities for the fields that still remain, even at the expense of those who live in those regions [17,18].

Ecuador is a typical example in which foreign companies have exploited oil in the Amazon, leaving enormous consequences such

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Combined multi-objective optimization and agent-based modeling for a 100% renewable island energy system considering power-to-gas technology and extreme weather conditions

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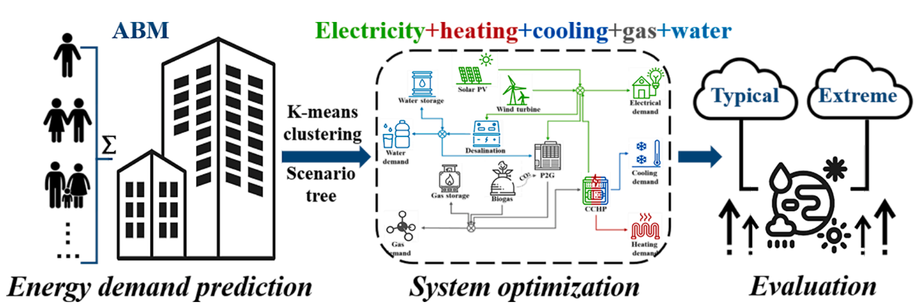
HIGHLIGHTS

- 100% renewable island energy system with P2G, biogas and desalination technologies.
- An integrated approach for demand prediction, design and dispatch optimization.
- Influence of extreme weather is considered.
- Desalination and biogas technologies can increase the resilience of the proposed system.
- P2G technology is more economic beneficial than battery storage for the case study.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Island energy system
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Power-to-gas
Extreme weather conditions

ABSTRACT

Islands are constrained by geographical conditions in terms of energy delivery. Due to weak connections with the mainland and the power grid, the diversity of island energy demand leads to high economic costs and environmental pollution issues. This study proposes a 100% renewable island energy system, which integrates with power-to-gas, combined cooling, heating and power, and desalination technologies to supply electricity, heating, cooling, gas and fresh water to the local residents. A comprehensive approach for energy demand prediction, system design and dispatch optimization, as well as system evaluation is proposed. For energy demand prediction, agent-based modeling is used to simulate the demand of electricity, heating, cooling, gas and fresh water for the case study community on the island. The k-means clustering and scenario tree are further adopted to generate representative stochastic scenarios, which are applied to capture the uncertainty of energy demand. A multi-objective optimization model is developed to optimize the system design and scheduling strategy simultaneously. In order to demonstrate the effectiveness of the proposed approach and to evaluate the obtained optimal solutions for the case study, different objectives and extreme weather conditions are specifically

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Towards 100% renewable islands in 2040 via generation expansion planning: The case of São Vicente, Cape Verde

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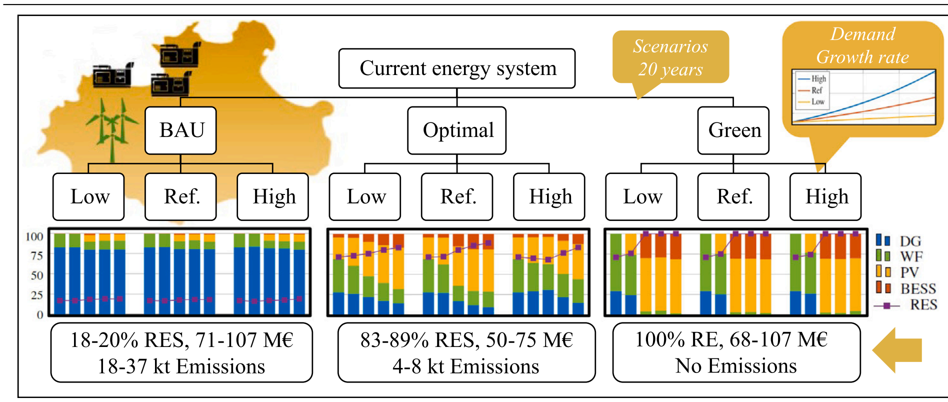
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Isolated power system
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ABSTRACT

In the energy transition context, islands are identified as particularly challenging regions due to their isolation, and energy dependence; while their excellent renewable resource and rapid growth makes them exceptionally interesting test cases. With the growing number of countries targeting 100% renewable penetration during the next decades, it is important to assess not only how to do so, but also whether we should. This paper focuses on the perspective of a generally overlooked set of regions; island developing nations. Their common challenges and energy policies are exemplified with a comprehensive generation and storage expansion planning (GSEP) for the island of São Vicente, Cape Verde. Formulated as an optimisation problem with hourly resolution, the GSEP minimises investment, maintenance, operation and emissions costs over a 20 year horizon from 2021. The extreme seasonal dependence of wind and solar resources is captured along with the operational dynamics of the generation and storage. Three scenarios are defined, one Business As Usual (BAU) keeping the current operational paradigm, another, Green, aligned with the local government goals, targeting 50 and 100% renewable shares in 2030 and 2040, and, lastly, one finding the Optimal. To reduce uncertainty influence, we consider three load growth levels for each scenario, defined based on expectations from national and international sources, corresponding to 1, 3 and 5%. The robust analysis obtained by combining scenarios and load levels provides a thorough view of Cape Verde's energy system to consider in future energy policy design. Green is the most expensive, BAU represents a 7% cost reduction, while Optimal a 30%, in addition to providing 90% renewable penetration, significant emissions reduction, and enough flexibility to modify the planning course if needed.

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A change in the air? The role of offshore wind in Australia's transition to a 100 % renewable grid

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ABSTRACT

Rapid decarbonisation of electricity production is required if Australia is to meet its obligations under the Paris Agreement. Critical to achieving this at low cost while maintaining system reliability is the selection of an appropriate mix of generation technologies to service electrical demand. Australia has seen extensive deployment of renewable energy technologies such as onshore wind and solar but has not yet seen the adoption of offshore wind technology. However, there is currently significant interest in developing this resource, with ongoing debate occurring about future technology costs and the potential of onshore renewables to meet electrical demand.

This article presents the results of an investigation into the techno-economic impact of exogenously fixing offshore wind capacity on a future least-cost Australian National Electricity Market with 100 % renewable generation. An existing open-source cost optimisation model, National Electricity Market Optimiser, was used for the study.

It was found that increasing the capacity of offshore wind in the generation mix leads to displacement of both onshore wind and solar generators. This is due to the greater magnitude and consistency of the offshore wind resource relative to onshore. Increasing offshore wind capacity therefore tends to reduce the total system generation capacity, as well as the amount of unused surplus generation. Using lowest published projections for future capital costs, inclusion of offshore wind was found to reduce total system costs. Using an average of future cost projections, total system costs were found to increase. However, adding up to 15 GW of offshore wind capacity to a 100 % renewable system would only impact total system costs by 5 %. Given the other potential advantages of offshore wind, namely closer siting to load centres, reduced need for onshore land resources, and the potential to transition existing fossil fuel workers, our results suggest that offshore wind may be a suitable candidate for inclusion in Australia's transition to a low carbon electricity system, under a range of future cost scenarios.

1. Introduction

Countries across the globe are aiming to reduce their greenhouse gas (GHG) emissions in the first half of this century to meet their international obligations under the Paris Agreement and avoid the worst effects of climate change. The current consensus is that a reduction to zero emissions must take place by around 2050 to have a chance of limiting warming to 1.5 °C (Espinosa, 2020). Given that emissions in some sectors of the economy are harder to abate than in others, it is likely that decarbonisation of electricity systems will need to occur prior to 2050. Pre-emptive decarbonisation of the electricity system will enable emissions reductions across the economy through electrification and the production of clean energy carriers such as green hydrogen.

Australia's emissions from electricity and heat production (EHP) are currently decreasing, while 'gross emissions' are increasing. The data from (Data) plotted below demonstrates this (Fig. 1). By gross emissions we refer to Australia's total GHG emissions minus discounting from land use, land use change and forestry (LULUCF). The ongoing increase in Australia's gross emissions, despite a reduction of GHG emissions from EHP, indicates that decarbonisation of EHP alone is insufficient to create the necessary trend to reach net zero emissions by 2050. This aligns with findings in the literature that the Australian economy will require

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Electrification of the industrial sector in 100% renewable energy scenarios

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A B S T R A C T

Future renewable energy systems with high shares of variable renewable energy production must also include technologies and measures to balance these production fluctuations. This could be in the form of electricity storage, energy demand adaptation (also known as demand-side management), or sector coupling. Industry electrification couples electricity and industry sectors by replacing the fossil fuel demand with electricity demands, thus enabling further integration of renewable electricity and transitioning the hard-to-abate energy sector. The effects of electrification on 100% renewable energy systems are rarely investigated. When investigated, one 100% renewable energy system scenario is used, which is often created by the same author, actor or organisation and may result in a narrow view of the possibilities for future energy systems. This study quantifies the role of industry electrification in the context of different 100% renewable energy system scenarios created by different relevant actors, to identify how its role may differ based on the scenario investigated. It is found that direct electrification of industrial process heat demands should be favoured over, e.g., a fuel shift to hydrogen-based process systems, even when these provide more flexibility.

1. Introduction

Worldwide, there is a shift towards renewable energy sources (RES). A shift in energy consumption from traditional fossil fuels to electricity in different energy sectors, such as the transport, heating and industry sectors, is an important part of the transition towards increased use of RES [1]. The types of RES expected to see the largest expansion globally are wind turbines (WT) and photovoltaic panels (PV). However, because of the variable nature of RES, an energy system built solely on variable renewable energy sources (VRE) also requires other changes to the energy system. Consequently, future renewable energy (RE) systems with high shares of VRE production will need to also include technologies and measures to balance these production fluctuations. This could be in the form of electricity storage or energy demand adaptation, also known as demand-side management or sector coupling solutions [2]. When considering such changes in the other parts of the energy system, previous studies on the transition towards 100% RE systems have found that to achieve a low-cost and energy-efficient transition, all energy sectors should be considered to maximise the potential integration and synergies between these, also in relation to the flexibility options [3]. Considering the entire energy system when transitioning to 100% RE systems is often referred to as the Smart Energy System approach, which was first introduced by Lund et al. [4].

When investigating future RE systems, energy system scenarios and energy planning models are often used [5,6]. These have become essential tools for quantifying the consequences of changes to energy systems. Despite modelling the same physical energy system, scenarios are inevitably influenced by the authors that make them, and even minor differences in their design and goals can cause ripple effects throughout the energy system, thereby complicating their comparison. The impact of different model assumptions and methodologies across different scenarios is rarely explored in detail and the reason behind the differences is not always transparent. Added to this is the influence of the different interpreting stakeholders of a scenario. Differences in the interpreting stakeholders' prior knowledge, their stake in the given

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energies

Article

A Backcasting Analysis toward a 100% Renewable Energy Transition by 2040 for Off-Grid Islands

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Abstract: The rapid increase in energy consumption results from population growth and technological advancement, while economic growth also relies heavily on the availability of energy. As fossil fuels become scarcer and greenhouse gas emissions increase, renewable energy sources are regarded as practical solutions to meet increasing energy demands. This study aims to develop a sustainable energy transition pathway for off-grid island communities in the Philippines. It adopts the concept of backcasting analysis, focusing on the demand and supply side of the energy transition. The transition considers three milestones: business as usual (BAU), minimal transition scenario (MTS), and absolute transition scenario (ATS). The techno-enviro-economic analysis is performed for each milestone to determine the optimal energy resource mix while addressing the three dimensions of the Energy Trilemma: energy security, energy equity, and environmental sustainability. The approach is implemented in three off-grid island municipalities in Palawan, Philippines: Araceli, Balabac, and Cuyo. The results suggest that the optimal electrification configuration for each island at the MTS is a hybrid system consisting of a diesel generator and solar photovoltaics with batteries, while at the ATS, it is a hybrid system of solar photovoltaics and wind with batteries. In addition, greenhouse gas emissions are reduced by 79.7% in Araceli, 78.7% in Balabac, and 41.2% in Cuyo from the BAU scenario to MTS. The actors involved in said transition are identified. A transitional pathway can be seen as a strategic plan to achieve the desired goal: to have a sustainable energy transition.

Keywords: hybrid renewable energy; HOMER; techno-enviro-economic analysis; simulation optimization; backcasting analysis

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1. Introduction

The continuous population growth and technological advancement have led to a rapid increase in energy consumption worldwide. The global energy demand increased an estimated 4.6% in 2021, more than offsetting the 4% contraction in 2020 [1], and fossil fuel is still the primary energy source at 84.3% [2]. However, burning fossil fuels for electricity generation contributes to environmental and social problems such as global warming, acid rain, and health-related issues for human beings [3]. The precipitous depletion of fossil deposits, coupled with climate change issues, has spurred countries worldwide to find solutions to transform the global electrification landscape and shift the dependence from conventional fossil fuels to renewable energy resources [4,5]. This has prompted various

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The bidding strategies of large-scale battery storage in 100% renewable smart energy systems

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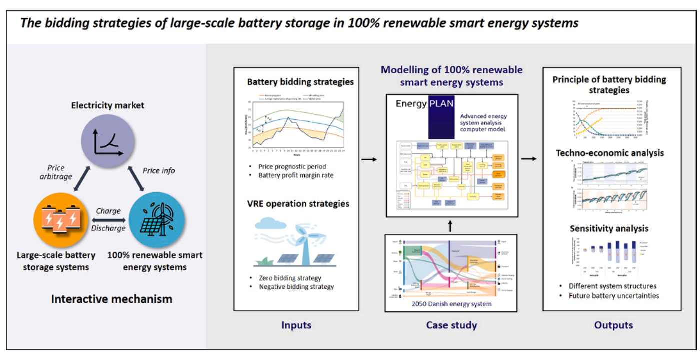
HIGHLIGHTS

- Bidding strategies of large-scale battery storage in 100% RE systems are studied.
- Hourly techno-economic analyses are conducted for both the battery and the energy system.
- The impacts of price prognostic period and battery profit margin rates are identified.
- Large-scale battery storage is not a necessity for the future 100% renewable smart energy systems.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Large-scale battery storage
Bidding strategy
Battery operation
Energy storage
100% renewable energy systems
Smart energy systems

ABSTRACT

Large-scale battery storage solutions have received wide interest as being one of the options to promote renewable energy (RE) penetration. The profitability of battery storages is affected by the bidding strategy adopted by the operator and is highly dependent on the operation of the rest of the energy system. Nevertheless, the coordination between the battery and the energy system has not been investigated in the literature yet. This paper provides a holistic hourly techno-economic analysis of the bidding strategies of large-scale Li-ion batteries in 100% renewable smart energy systems. As a case study, the 2050 Danish energy system is used to demonstrate the relationship between large-scale battery systems and the rest of the energy system. The results show that large-scale battery storage plays a limited role in future energy systems that follow the smart energy system concept. Likewise, the battery solution is only economically feasible in the Danish smart energy system at low battery storage capacities (few hours' duration) with a low-profit margin rate (approx. 100%) and a short prognostic period (approx. 12 h) for operation planning. The finding of this study provides the general strategies of the battery bidding and operation in 100% RE systems.

1. Introduction

Accelerating the energy transition towards a 100% renewable energy

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Fully electrified land transport in 100% renewable electricity networks dominated by variable generation

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ABSTRACT

Large greenhouse gas reductions are possible with a fully decarbonised grid and electric land transport. Additional electric load could pose a significant challenge to a grid with high levels of variable and non-dispatchable renewable energy sources. This scenario is not well-examined, nor is the use of pumped hydro energy storage for low-cost energy balancing. In this paper, we investigate the electrification of land transport within a photovoltaics and wind dominated 100% renewable electricity system. Only technologies that are deployed at scale and widely available globally are considered, namely photovoltaics, wind, battery electric vehicles, high voltage transmission, and pumped hydro. As a case study we present an hourly energy balance analysis of the Australian National Electricity Market with 100% renewables and 100% uptake of electric vehicles for land transport. The cost of the system is determined by occasional periods (days-weeks) of low renewable generation, and therefore only weakly dependent on the charging regime. The 40% increase in electricity demand due to electric land transport can be incorporated with a 4%–8% increase in the levelized cost of electricity. An exception occurs if most passenger vehicle charging occurs during the evening peak period, in which case the average price increases by about 18%.

1. Introduction

To limit global warming to well below 2 °C, and as close to 1.5 °C as possible [1], it is necessary to stop using fossil fuels, preferably while also providing an equitable energy supply to all of humanity. The stunning declines in the cost of solar photovoltaics (PV) and wind mean these technologies are now competitive with new-build coal- and gas-fired power, and it is expected that they will cost less than the operating costs of existing fossil plants within a decade [2]. In 2019, over 160 Gigawatt (GW) of net new wind and PV [3] was deployed, which is more than the sum of coal [4], gas, nuclear [5] and other renewables [3] combined. The decarbonisation of the current electricity system via PV and wind and sufficient storage is feasible at low net cost [6] but could be complicated by the inclusion of large new loads, such as the electrification of transport.

Renewable electrification of land transport via electric vehicles (EV) would reduce greenhouse emissions by 15–25% globally [7]. For example, Khalili et al. [8] showed that fuel switching in all modes of land, sea, and air transport could assist in limiting warming to 1.5 °C, although this work did not include the embodied carbon of the electrified fleet. Electrifying the land transport fleet would likely reduce total energy consumption, oil spills, oil-related conflict, and improve urban air pollution and local energy security. However, other problems remain: noise pollution, traffic accidents, reduced opportunities for walking and cycling, air pollution due to brake pad and tyre degradation, the assignment of a large fraction of city space to car parking and roads, and the consequent urban heat effect.

If the only problem were one of short term supply, the additional demand due to the electrification of land transport could be met relatively simply with fossil fuels and dispatchable hydro: more coal, gas, or hydro capacity could be added and managed to follow the load. This is, however, more complicated in an electricity system dominated (>90%) by variable PV and wind, as the additional demand would require not only more PV and wind capacity, but also more storage and dispatchable generation capacity. It is important to determine how much more (if any) this would be likely to cost.

In this paper we explore the renewable electrification of land

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Mitigation of carbon footprint with 100% renewable energy system by 2050: The case of Galapagos islands

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A B S T R A C T

In this paper, a technical-economic study of the 100% renewable energy sources in the Galapagos islands is done. Historical consumption data for 2011–2020 have been considered to forecast the load curve. To achieve this goal, the load is forecasting by Nonlinear autoregressive exogenous neuronal network model for 2030 and 2050. The study focuses on supplying the energy demand of the islands with renewable sources, analyzing possible scenarios based on the current electricity system. The methodology studies the capacity of renewable sources to balance supply and demand through dispatch simulations using the EnergyPLAN software. The results show energy flows, costs and long-term energy balances (2050), with 100% renewable energy from several wind and photovoltaic combinations. Moreover, The precision of the demand forecast was 98.12% with a mean square error of 0.013%. The total annual cost decreases while the capacities of the renewable sources increase to a certain point of equilibrium. As salient features of the developed approach, various sensitivity analyzes are presented that allow understanding the uncertainties, scope and limitations of the proposed models.

1. Introduction

Climate change is a global problem, which is caused both by the increase in temperature on the planet and by the carbon dioxide (CO_2) emissions that contribute significantly to the greenhouse effect. Environmental improvement has several fronts and challenges, from efficiency related to production cycles in agriculture [1], urban solid waste management [2], control of water resources for irrigation [3], sustainable production of inputs necessary for human beings [4], among others. A sustainable energy system must be able to produce its supply chain by reducing emissions of polluting gases [5], using abundant natural resources to generate electricity for its applications [6]. Generally, to improve the sustainability of an energy system and the environment, alternatives should be considered that allow reducing gas emissions to the atmosphere in the coming years, being fundamental the use of renewable energy sources (RES) [7]. The generation of electrical energy with RES is intermittent, this produces a difficult technical challenge to solve, adjusting the generation to the demand. To deal with this problem in long-term energy planning, the size of renewable sources, storage systems, and the analysis of different control systems are considered [8].

Currently, the energy supply of the small islands is based on diesel generators (DG), which causes a greater dependence on imported fossil fuels, and this causes CO_2 emissions to increase and also the cost of generation [9]. Unfortunately, because the geographic location and the size of the Pacific islands, the available energy sources are limited [10]. Electricity generation costs in this area are approximately 45 USc/kWh. The cost is relatively high because of fuels transportation. However, the Pacific islands have sufficient renewable resources, especially solar and wind energy, that could reduce current generation costs [11]. In this way, it would be promising to analyze hybrid renewable energy systems (HRES) that can supply even 100% of the demand, which would lead to even more ecological and in some cases more economical electrical systems [12]. Because poor policies and low investments in the energy context, the development and awareness of renewable energy is still scarce. Despite this, in the literature there are several studies based on renewable sources and isolated systems that increasingly promote the use of RES to reduce the consumption of fossil fuels. It is the case of Eras-Almeida et al. [12], the authors present a study of 10 small off grid islands (Atlantic and Arctic, Pacific and Indian Oceans, Caribbean Sea and Mediterranean) where a 100% renewable generation system could be implemented using

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Transition pathway towards 100% renewable energy across the sectors of power, heat, transport, and desalination for the Philippines

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ABSTRACT

Transition towards sustainable energy systems is of utmost importance to avert global consequences of climate change. Within the framework of the Paris Agreement and Marrakech Communique, this study analyses an energy transition pathway utilising renewable resources for the Philippines. The transition study is performed from 2015 to 2050 on a high temporal and spatial resolution data, using a linear optimisation tool. From the results of this study, technically, a 100% fossil free energy system in 2050 is possible, with a cost structure comparable to an energy system in 2015, while having zero greenhouse gas emissions. Solar PV as a generation and batteries a as storage technology form the backbone of the energy system during the transition. Direct and indirect electrification across all sectors would result in an efficiency gain of more than 50% in 2050, while keeping the total annual investment within 20–55 b€. Heat pumps, electrical heating, and solar thermal technologies would supply heat, whereas, direct electricity and synthetic fuels would fuel the energy needs of the transport sector. The results indicate that, indigenous renewable resources in the Philippines could power the demand from all energy sectors, thereby, bringing various socio-economic benefits.

1. Introduction

There is a consensus among nations to transform the global energy systems mainly relying on finite fossil fuels towards utilising renewable and sustainable resources to avert the irreversible effects of anthropogenic climate change [1]. While some countries are taking lead in renewable energy (RE) utilisation, concurrent global efforts are still missing as seen from increasing greenhouse gas (GHG) emissions [2] Consequently, a growing number of catastrophic climate change events are common occurrences in different parts of the world. The Philippines, a country with 7641 islands, is cited as one of the most susceptible countries to climate change [3], exposing itself to super typhoons [4], rising sea levels [5], and droughts [6]. For the Philippines, transforming its energy system by utilising higher shares of renewable resources would help decreasing GHG emissions and consequently mitigating these vulnerabilities.

Transition towards utilising higher share of renewables, however, requires an overhaul of the current fossil fuel-based energy system. Besides being highly efficient, the energy system should be a new combination of several renewable technologies. For example, solar photovoltaics (PV) is likely to play a major role in the electricity production [7,8] on a global scale, followed by wind energy and other sustainable technologies. Simultaneously, technologies, like heat pumps, electrical heating, and electric vehicles, would make the heat and transport sectors more efficient. Furthermore, flexibility provided by bridging and storage solutions, would ensure security of energy supply of Variable Renewable Rnergy (VRE) technologies. Finally, an integrated all energy sector transition towards 100% RE is complex, however studies for the entire planet [9–12] and country-level studies for Chile [13], Bolivia [14], Ethiopia [15] and Jordan [16] have shown that it is technically and economically possible.

In this research, a 100% renewable energy transition pathway for the Philippines was simulated using the LUT Energy System Transition model [9,12,17]. The energy sectors power, heat, transport and desalination were realised, and their complex interaction was studied.

The paper is structured as follows. Section 1.1 describes the Philippine energy system structure. The energy planning and motivations are given in Section 1.2, and Section 1.3 tackles the historical context of the Philippine energy sector. Section 1.4 describes the Philippine energy

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Proposal of 100% renewable energy production for the City of Cuenca-Ecuador by 2050

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A B S T R A C T

This research presents a scenario for a 100% renewable energy system for the City of Cuenca, Ecuador, with a projection to the year 2050. The transition process starts with Ecuador's change in the productive matrix with reforms from the legal and business strategies point of view to the year 2050. Advances in energy material are dependent on political uncertainty both at the country (Ecuador) and local (Cuenca) levels. It is possible to stop using fossil fuels due to the implementation of new renewable energy sources, potentially rich in the Ecuadorian Southwest and evidenced in the National Plan for a Lifetime. Currently, there is evidence of accelerated changes concerning legal regulations, including the construction of several electric power generation plants. This change in the national productive matrix implies, among others, the implementation of electric vehicles and the change of natural gas stoves for electric ones, and the implementation of the "4 Rios" tram that crosses the city from North-South and South-North, incorporating 100% renewable energy generation, which would provide heat in urban and marginal urban areas. All the systems created in Ecuador, such as heating, cooling, transportation, security etc., will allow an increasing penetration of renewable energy until it reaches 100%.

1. Introduction

The need for adequate energy supply brings the attention of millions of people around the world [1,2]. The fuel is used in various fields of daily life. Its uses bring increasing ecological and social problems, including human interaction with nature [3]. At the beginning of the 21st century, industrialization accelerated processes intending to massively extract fossil fuels to a level that alarms the international community [4]. Global climate change also includes the problem of fossil fuel shortages [5]. A clear example is the one currently experienced in Ecuador, where oil reserves are depleting at an accelerated rate and national and foreign companies have paid attention to oil reserves in the Eastern Amazon, such as the Yasuní ITT where flora, fauna and uncontacted peoples see a permanent threat that their natural habitat is destroyed by extractivists [6,7]. In 2011, Ecuador launched the initiative that promotes stopping climate change seeking to create a new paradigm, known as the Yasuní-ITT initiative [8–11], which consisted of leaving part of its reserves in perpetuity, untapped and underground. Oil companies in one of the most biodiverse areas in the world, committing not to exploit the crude oil from the Ishpingo-Tambococha-Tiputini (ITT) field located in the Yasuní National Park, in the Ecuadorian Amazon in exchange for economic compensation from governments, institutions and even citizens of any part of the world [8]. This idea considered innovative had the concept of leaving oil underground, considered 20% of Ecuador's oil reserves, almost one billion barrels, to avoid the emission of 410 million tons of CO_2 into the atmosphere, as told BBC World the former mayor of Quito Roque Sevilla [9,10].

The Yasuní National Park breaks all records of species concentration. For example, in 1 ha, we have more than 650 species of trees, compared to a thousand species that exist throughout North America [8,9]. Finally, this initiative did not manage to obtain sufficient resources to leave the crude oil on land, nor has the ITT field been exploited, there are still several countries that are supporting the continuation of this initiative for the good of humanity [10,11]. Regarding the structure of the paper, in this first section we address the current energy situation in which Ecuador and the world are immersed in trying to fight global warming. Section 2 refers to the methodology used in this research. Section 3 analyzes the different energy sources potentially usable for supplying the City of Cuenca.

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Full energy sector transition towards 100% renewable energy supply: Integrating power, heat, transport and industry sectors including desalination

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HIGHLIGHTS

- Sector coupling leads to lower cost of energy supply in a RE-based system.
- Power sector becomes the backbone of the entire energy system.
- Integration impact depends on demand profiles, flexibility and storage cost.
- Electrolysers are an important source of flexibility in an integrated system.
- All sector defossilisation is achieved even for severe conditions as of Kazakhstan.

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Keywords:
100% renewable energy
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ABSTRACT

Transition towards long-term sustainable energy systems is one of the biggest challenges faced by the global society. By 2050, not only greenhouse gas emissions have to be eliminated in all energy sectors: power, heat, transport and industry but also these sectors should be closely coupled allowing maximum synergy effects and efficiency. A tool allowing modelling of complex energy system transition for power, heat, transport and industry sectors, responsible for over 75% of the CO_{2eq} emissions, in full hourly resolution, is presented in this research and tested for the case of Kazakhstan. The results show that transition towards a 100% sustainable and renewable energy based system by 2050 is possible even for the case of severe climate conditions and an energy intensive industry, observed in Kazakhstan. The power sector becomes backbone of the entire energy system, due to more intense electrification induced sector coupling. The results show that electrification and integration of sectors enables additional flexibility, leading to more efficient systems and lower energy supply cost, even though integration effect varies from sector to sector. The levelised cost of electricity can be reduced from 62 €/MWh in 2015 to 46 €/MWh in 2050 in a fully integrated system, while the cost of heat stays on a comparable level within the range of 30–35 €/MWh, leading to an energy system cost on a level of 40–45 €/MWh. Transition towards 100% renewable energy supply shrinks CO_{2eq} emissions from these sectors to zero in 2050 with 90% of the reduction achieved by 2040.

1. Introduction

Ongoing growth in anthropogenic greenhouse gas (GHG) emissions is one of the greatest threats to civilization. Despite the consensus that GHG emissions should be eliminated by 2050 in order to fulfil the Paris Agreement and limit global temperature rise to the well below 2 °C level [1], consumption of fossil fuels is growing in all energy sectors [2]. To complicate matters even further, major countries are falling short of their GHG reduction commitments, raising concerns that even a 2 °C target may be out of reach [3]. Growing number of evidence from significant climate change effects like temperature deviations from a long term climatic norm for an area [4,5], collapsing sea [6] and land ecosystems [7], and irregular monsoons are common occurrences in different parts of the world, while this process is projected to accelerate in the future [8] without immediate and adequate actions [9]. As a response, society and general public are showing renewed interest in climate change mitigation questions: particularly, increasing number of

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Robust design of a future 100% renewable european energy supply system with hydrogen infrastructure

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HIGHLIGHTS

- A fully renewable European energy system with hydrogen infrastructure is attained.
- Higher resolution of renewables in a region decreases the total annual costs.
- Hydrogen production occurs mainly in the regions with cheaper electricity cost.
- Wind and solar energies are complementary generation technologies in the system.

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ABSTRACT

Variable renewable energy sources (VRES) will be the cornerstones of future energy supply systems. Nevertheless, their inherent intermittency remains an obstacle to their widespread deployment. Renewably-produced or ‘green’ hydrogen has been suggested as an energy carrier that could account for this in a sustainable manner. In this study, a fully VRES-based European energy system in the year 2050 is designed using an iterative minimal cost-optimization approach that ensures robust supply security across 38 weather-year scenarios (1980–2017). The impact of different power generation locations is factored in by defining exclusive VRES groups within each optimization region. From this, it can be seen that higher numbers of groups in each region offer cheaper electricity generation locations to the optimizer and thus decrease the system's total annual costs. Furthermore, the robust system design and impact of inter-annual variability is identified by iteratively combining the installed capacities of different system designs derived through the application of the 38 historical weather years. The system design outlined here has significantly lower capacities in comparison to the maximum regional capacities obtained in the first round of optimization.

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Open model-based analysis of a 100% renewable and sector-coupled energy system–The case of Germany in 2050

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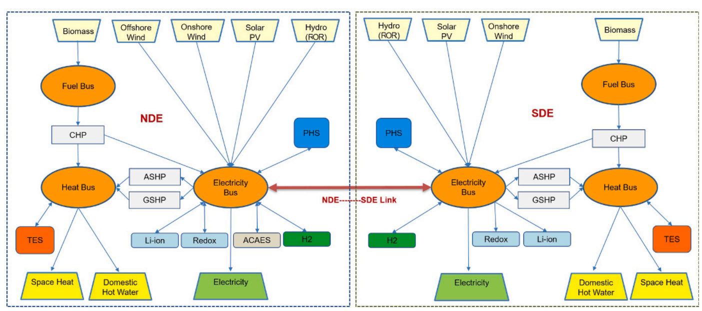
HIGHLIGHTS

- Open model-based analysis for 100% renewable and sector-coupled energy systems.
- Cost-optimization tool based on Oemof to investigate Germany's energy system in 2050.
- Renewable energy is sufficient for electricity and building heat in Germany in 2050.
- Investment cost (bn €/yr): 17.6–26.6 (Volatile), 23.7–28.8 (Heat), 2.7–3.9 (Storage).
- Energy mix and LCOE comparison validate the developed tool's effectiveness.

GRAPHICAL ABSTRACT



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Keywords:
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ABSTRACT

The ambitious energy target to achieve climate-neutrality in the European Union (EU) energy system raises the feasibility question of using only renewables across all energy sectors. As one of the EU's leading industrialized countries, Germany has adopted several climate-action plans for the realistic implementation and maximum utilization of renewable energies in its energy system. The literature review shows a clear gap in comprehensive techniques describing an open modeling approach for analyzing fully renewable and sector-coupled energy systems. This paper outlines a method for analyzing the 100% renewable-based and sector-coupled energy system's feasibility in Germany. Based on the open energy modeling framework, an hourly optimization tool 'OSeEM-DE' is developed to investigate the German energy system. The model results show that a 100% renewable-based and sector-coupled system for electricity and building heat is feasible in Germany. The investment capacities and component costs depend on the parametric variations of the developed scenarios. The annual investment costs vary between 17.6 and 26.6 bn €/yr for volatile generators and between 23.7 and 28.8 bn €/yr for heat generators. The model suggests an investment of a minimum of 2.7–3.9 bn €/yr for electricity and heat storage. Comparison of OSeEM-DE results with recent studies validates the percentage-wise energy mix composition and the calculated Levelized Cost of Electricity (LCOE) values from the model. Sensitivity analyses indicate that storage and grid expansion maximize the system's flexibility and decrease the investment cost. The study concludes by showing how the tool can analyze different energy systems in the EU context.

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Techno-economic optimization of a 100% renewable energy system in 2050 for countries with high shares of hydropower: The case of Portugal

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A B S T R A C T

As energy system will increasingly become renewable, they will face new challenges that mainly arise due to the varying output by many renewable energy technologies. An issue that is especially prominent for countries with high shares of hydropower in their electricity generation is the varying yearly output of these technologies. This work aims to propose a techno-economically optimized energy system for such a country, using Portugal as example. For this purpose the current situation is analyzed and an energy demand model for 2050 created. The energy system is optimized for years with different outputs of hydropower to analyze the system's behavior using the simulation tool EnergyPLAN. As the tool does not possess inherent optimization capabilities it was coupled with the gray wolf optimization algorithm using Matlab. Subsequently, a system is proposed that is able to cover Portugal's expected energy demand under all circumstances. The future system will rely strongly on wind and solar power as they are expected to cover around 75% of Portugal's electricity demand. Furthermore, the analysis showed that Portugal needs to build up electrolyzer capacities of 4.2 GW and SynGas capacities of 2.4 GW as the SynGas will be used to balance supply in demand, especially in years with lower hydropower output. The system's cost will be between 22 and 35% cheaper than the created reference model. Furthermore, the primary energy demand is expected to decrease from 253 TWh to around 150 TWh while the electricity demand rises from 49 TWh to around 110 TWh.

1. Introduction

As counter measurement against climate change, most of the countries in the world signed the Paris agreement in 2015. These countries pledged to strongly reduce its greenhouse gas (GHG) emissions to limit the anthropogenic climate change to ideally 1.5 °C Hence the European Union set the goal to reduce GHG emissions by 80–95% until 2050 in comparison to the base year 1990 [1]. For Portugal this corresponds to a maximum GHG emissions of 11.9 million tons of CO_{2eq} by 2050 to reach an 80% reduction. As shown in Fig. 1, the energy sector is responsible for ca. 70% of Portugal's entire GHG emissions [2]. Thus, it is the biggest lever to decrease emissions.

To reach significant reductions, this requires a significant use of renewable energy sources. This poses new challenges as, except for biomass, the output of renewable technologies cannot be adjusted to the demand. This causes a paradigm shift to a fossil-based energy system where supply followed demand. The timescale and the amplitude of these variations differ from technology to technology [3]. Regarding hydropower the most notable issue is the varying output on a yearly timescale. The hydropower capability index (CI), which indicates the output, can change from one year to another by

Abbreviations: APA, Portuguese Environmental Agency; APREN, Renewable Energy Association; CAES, compressed air energy storage; CCS, carbon capture & storage; CEEP, critical excess energy production; CHP, combined heat and power; CI, capability index; COP, coefficient of performance; CSP, concentrated solar power; DSM, demand-side management; GHG, greenhouse gas; GWO, gray wolf algorithm; H&C, heating & cooling; HDR, hot dry rock; PHES, pumped hydro energy storage; PtG, power-to-gas; PV, photovoltaics; RE, renewable energy; SynGas, synthetic gas.

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A Demand-Supply Matching-Based Approach for Mapping Renewable Resources Towards 100% Renewable Grids in 2050

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ABSTRACT Recently, many renewable energy (RE) initiatives around the world are based on general frameworks that accommodate the regional assessment taking into account the mismatch of supply and demand with pre-set goals to reduce energy costs and harmful emissions. Hence, relying entirely on individual assessment and RE deployment scenarios may not be effective. Instead, developing a multi-faceted RE assessment framework is vital to achieving these goals. In this study, a regional RE assessment approach is presented taking into account the mismatch of supply and demand with an emphasis on Photovoltaic (PV) and wind turbine systems. The study incorporates mapping of renewable resources optimized capacities for different configurations of PV and wind systems for multiple sites via test case. This approach not only optimizes system size but also provides the appropriate size at which the maximum renewable energy fraction in the regional power generation mix is maximized while reducing energy costs using MATLAB's ParetoSearch algorithm. The performance of the proposed approach is tested in a realistic test site, and the results demonstrate the potential for maximizing the RE share compared to the achievable previously reported fractions. The results indicate the importance of resource mapping based on energy-demand matching rather than a quantitative assessment of anchorage sites. In the examined case study, the new assessment approach led to the identification of the best location for installing a hybrid PV / wind system with a storage system capable of achieving a nearly 100% autonomous RE system with Levelized cost of electricity of 0.05 USD/kWh.

INDEX TERMS Renewable energy resources, multi-objective optimization, energy demand matching, resources assessment, resources geographical mapping.

I. INTRODUCTION

Recently, the energy market witnessed a significant decline in the adaptation of distributed energy resources (DERs) such as wind turbines and solar Photovoltaics (PV) due to the impacts of the novel COVID-19 on the world's economy. With the global crisis, energy demand has dropped down in the industrial and commercial sectors, in contrary, the load increased in the residential sector. Therefore, governments had to put new strategies to tackle down the ongoing challenges. Elavarasan *et al.* [1] studied the impact of COVID-19 pandemic on the power sector for the Indian power grid. Their work investigated global scenarios along with the social-economic and technical issues encountered by utilities.

According to [2], 40% of the RE integration plans in 2020 were suspended. Yet, the same article emphasizes that the economic advantages of clean energy production methods possess a long-term value compared to fossil-fuel-based

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Towards a 100% renewable energy electricity generation system in Sweden

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Energy storage

ABSTRACT

Swedish government's target is to have 100% renewable electricity production by 2040. Currently, hydropower contributes the majority of renewable electricity generation of the country. The wind power capacity has increased significantly in the past decade. In this paper, practical data is used to study the possibility of reaching the 100% renewable electricity generation goal by replacing existing thermal generations with wind power generations. It is found that the Swedish electricity generation system can reach 100% renewable by tripling the existing wind power capacity combined with the existing hydropower in the country. Based on current growth rate of wind power installation, the goal could be reached within 20 years. Hourly simulation shows that 100% renewable energy generation system composed by wind power and hydropower satisfy hourly operation requirements.

1. Introduction

Transitioning the global economy to sustainable development is one of the challenges in the coming decades. In 2015, the United Nations (UN) adopted the 2030 Agenda for Sustainable Development, which includes the Sustainable Development Goals (SDG) to achieve a better and more sustainable future [1]. Among the 17 goals, the seventh goal, SDG 7, is "*ensure access to affordable, reliable, sustainable and modern energy for all* [2]." It encourages a more sustainable energy system available widely. The UN has defined 5 targets and 7 indicators for SDG 7. The targets include: increase the share of renewable energy in the global energy mix, improve the energy efficiency, and promote investment in clean energy technology, etc., by 2030 [3]. The transition to a renewable based energy system is the path to achieve SDG 7 providing affordable and clean energy. Renewable energy could be utilized directly, such as, burning biomass or biogas, converting solar energy to thermal energy, converting wind power and hydro power to kinetic energy, using heat pump for space heating, etc. For electricity users, renewable energy could be electric energy generated from flowing water, wind, sunlight, biomass, or other sources like, wave energy, hydrogen, etc.

Renewable energy is a promising solution to a number of environmental and energy problems currently facing the world. Governments of different countries have set targets for the percentage of energy to be produced from renewable sources for future decades. In some regions, the goal is to have 100% of energy consumption from renewable sources in 20–30 years. The Swedish government has an ambitious goal that 100% of Swedish electricity consumption will come from renewable sources by 2040. Denmark sets the date of 100% renewable energy to 2050 [4]. Iceland is already producing 100% renewable energy electricity from hydropower and geothermal. Norway has around 97% of electricity from hydropower [5]. The transition to 100% renewable energy is underway in some areas. Scotland aims to generate all electricity from renewable sources by 2020s. Dutch railway system and trains are 100% powered by wind energy. California State has set a goal of 100% renewable and zero-carbon electricity by 2045, while Massachusetts State has the goal of 100% renewable energy by 2050. Other states are following. Renewable energy targets worldwide and their ongoing progresses are discussed in Ref. [6]. It shows that 100% renewable energy system is no longer an unrealistic vision to governments, while academics are discussing the feasibilities.

Technically, Jacobson et al. [7] modelled the renewable energy potential in California, and concluded that California can meet more than 99% of its energy demand with wind, water and sunlight by making an optimized usage of demand management, various

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On the correlation between building heat demand and wind energy supply and how it helps to avoid blackouts

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A B S T R A C T

Keeping the electric and heat grids stable is the major challenge facing the world as it transitions away from fossil fuels to electricity and heat provided by wind, water, and sunlight (WWS). Because building heating and cooling demands and wind and solar energy supplies both depend on the same weather, building demands should be modeled consistently with renewable supplies. However, no model to date has calculated future thermal loads consistently with future renewable supplies. Here, a global weather/climate model is used to do this. Grid stability in 24 world regions encompassing 143 countries is then examined. Low cost solutions are found everywhere. Building heat loads are found to correlate strongly with wind energy supply aggregated over large, cold regions. Moderate correlations are found elsewhere, except no correlation is found in some tropical islands and some small countries. Thus, wind energy in most climates can help to meet seasonal heat loads, thereby helping to reduce the cost of energy. Finally, wind and solar power supplies are negatively correlated, indicating that wind and solar are complementary in nature and should both be built, where feasible, to reduce output variability arising from installing only one of them.

In order to reduce substantially or eliminate the seven million annual air pollution deaths, global warming, and energy insecurity that arise from fossil fuel use, the world is transitioning all energy sectors toward clean, renewable electricity and heat. However, a major concern is whether heat demand in buildings can be met every minute with renewable electricity and direct heat supply. An additional question is whether all energy demand can be met every minute with clean, renewable electricity and heat supply. This study addresses both issues. It first uses a global weather-climate model to simulate future building heat and cold demands worldwide consistently with wind and solar supply. In doing so, it finds a strong positive correlation between wind supply, aggregated over large, cold regions, and building heat demand in the same regions. It also finds weak negative correlations between wind supply and building cold demand and between wind supply and solar supply. The latter anticorrelation suggests wind and solar supplies are complementary in nature. Finally, the data are used to find low-cost solutions to grid stability in 24 world regions encompassing 143 countries. The study concludes that, due to the strong correlation between wind supply and heat demand, wind energy in most climates can help to meet seasonal heat demand while reducing the cost of energy.

1. Introduction

Many studies have examined the feasibility of matching electricity and/or heat demand with supply, storage, and/or demand response upon transitioning one or more energy sectors entirely to 100% renewable energy. Some of these studies quantified installations needed to match annual-average demand among all energy sectors (electricity, buildings, transportation, industry, etc.) worldwide or in most countries with renewable supply [1,2]. Others quantified installations needed to meet demand continuously worldwide among all energy sectors [3–5]; in one country in the electric power sector [6–15], in one country among multiple energy sectors [16–22]; on the continental scale in the electric power sector [23,24], or on the continental scale among multiple sectors [25,26].

Studies that treated multiple sectors assumed that heating was electrified through the use of either electric heat pumps or resistance heating. Some studies that treated the electrification of heating also considered district heating and/or energy efficiency/weatherization measures to reduce heat demand in buildings. All

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Towards sustainable development in the MENA region: Analysing the feasibility of a 100% renewable electricity system in 2030

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ABSTRACT

This research explores the feasibility of 100% renewable energy (RE) systems for the Middle East and North Africa (MENA) region for assumptions of the year 2030. The demand for three sectors are taken into account: power, non-energetic industrial gas and seawater desalination. Three strategical scenarios are discussed, namely Region, Area and Integrated, mainly differing in level of regional grid interconnection and sector coupling. Solar photovoltaics (PV) and wind energy are found to be the most cost-competitive RE sources with the highest potential in the region covering more than 90% of the generation capacity in all the considered scenarios. The variability of RE is solved via energy storage, surplus electricity generation and electricity grids. The estimated overall levelised cost of electricity (LCOE) lies between 40.3 and 52.8 €/MWh, depending on the scenarios. The total LCOE decreased by 17% as a result of sector coupling compared to the interconnected power sector alone. Power-to-gas technology not only functions as a seasonal storage by storing surplus electricity produced mainly from wind power and partially from solar PV, but provides also the required gas for the non-energetic industrial gas sector. Battery storage complements solar PV as a diurnal storage to meet the electricity demand during the evening and night time. Seawater reverse osmosis desalination powered by renewables could potentially be a proper solution to overcome the water challenges in the MENA region at affordable cost of 1.4 €/m^3. A comparison with a BAU strategy shows that a 100% renewable energy-based power system is 55–69% cheaper than a BAU strategy without and with greenhouse gas emission costs.

1. Introduction

The energy demand in the Middle East and North Africa (MENA) is increasing swiftly. This is largely because of population growth, socio-economic development and urbanisation, driven both by oil and gas revenues, and by growth-oriented policies [1]. In addition, countries in the region offer the highest energy subsidies globally. This helps to explain the high electricity demand and carbon dioxide (CO_2) emissions per capita prevalent [2]. In 2014, around 51% of CO_2 emissions from total fuel combustion in the MENA region was from electricity and heat production [3].

The MENA region contributes considerably to oil and gas production globally by holding a high share of proven crude oil and natural gas reserves [4–6]. A strong connection between fossil fuels and socio-economic development make the region highly vulnerable to the impacts of climate change [7]. Increasing global temperatures will have devastating effects such as more intense heat waves, severe droughts and decreasing the amount of precipitation [8]. This would mean a rise in demand for water desalination and air conditioning, in a region that is one of the most water-stressed in the world [9,10].

At present, renewable energy (RE) sources have a minor contribution, around 0.4%, to the total primary energy supply (TPES) in the MENA region [11,12]. Most of the countries rely on natural gas and oil to generate electricity. This reliance is expected to continue until 2030 [6]. Nonetheless, increasing costs of fossil fuels, decreasing costs of RE technologies, new RE targets and policies have resulted in an increase in the share of RE capacity in the power sector by 56% from 2008 to 2016 [13]. Among all RE sources, solar and wind energy offer the highest potential in the region. The national RE targets [13] and various projects in the pipeline reveal that noticeable RE development and deployment is well underway in the MENA region. This trend is expected to continue in the future as well [14]. Table 1 summarises the strategy and targets of RE development in each country, including the specified technologies and allocated years. It should be noted that some countries in the MENA region have agreed to use 100% RE by 2050 [15], but yet do not have a strategy. These countries are: Morocco, Tunisia, Yemen, Lebanon and State of Palestine.

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Article

100% Renewable Energy Scenarios for North America—Spatial Distribution and Network Constraints

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Abstract: The urgency to combat climate change and the widely distributed, increasingly competitive renewable resources in North America are strong arguments to explore scenarios for a renewable energy supply in the region. While the current power system of North America is heavily dependent on fossil fuels, namely natural gas, coal and oil, and some nuclear power plants, some current policies at the state level, and future federal policies are likely to push the share of different renewable sources available in Mexico, the U.S., and Canada. This paper explores three scenarios for a renewable energy supply, using a bottom-up energy system model with a high level of spatial and time granularity. The scenarios span the extremes with respect to connecting infrastructure: while one scenario only looks at state-level supply and demand, without interconnections, the other extreme scenario allows cross-continental network investments. The model results indicate that the North American continent (a) has sufficient renewable potential to satisfy its energy demand with renewables, independent of the underlying grid assumption, (b) solar generation dominates the generation mix as the least-cost option under given renewable resource availability and (c) simultaneous planning of generation and transmission capacity expansion does not result in high grid investments, but the necessary flexibility to integrate intermittent renewable generation is rather provided by the existing grid in combination with short-term and seasonal storages.

Keywords: 100 percent renewable energies; capacity expansion modeling; electricity market integration

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1. Introduction

Shortly before political leaders from all over the world gathered for the Copenhagen Summit in 2009, Jacobson and Delucchi [1] published an article with a roadmap towards a worldwide, 100 percent renewable energy system by 2030. Although the overall capacity of Renewable Energies (RE) has been gradually increasing and several countries have committed to ambitious climate targets since then, today's total energy supply is still primarily met by fossil fuels and the world is facing a prevailing, massive emission gap in reaching the Paris Climate agreement [2,3]. As the current scientific and public debate discusses several mitigation options for the energy sector, the recent scientific research on a large-scale deployment of RE suggests that RE are becoming more cost-efficient than electricity generation from fossil fuels, even without including the social cost of carbon emissions and including the intermittent nature of RE [4].

With a share of approximately one-fifth of the global primary energy demand, North America is the second-largest consumer and producer of energy in the world [5]. As illustrated in Figure 1, the electricity generation in the United States (U.S.) and Mexico still depends mainly on fossil gas, coal, and nuclear power, while Canada already utilizes its potential for hydro generation. However, the framework for power generation is gradually changing towards increasing shares of RE, as in the recent Clean Power Plan announced by

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Transition towards decarbonised power systems and its socio-economic impacts in West Africa

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ABSTRACT

Pathways towards a defossilated sustainable power system for West Africa within the time horizon of 2015–2050 is researched, by applying linear optimisation modelling to determine the cost optimal generation mix to meet the demand based on assumed costs and technologies in 5-year intervals. Six scenarios were developed, which aimed at examining the impact of various policy constraints such as cross-border electricity trade and greenhouse gas emissions costs. Solar PV emerges as the prime source of West Africa's future power system, supplying about 81–85% of the demand in the Best Policy Scenarios for 2050. The resulting optimisation suggests that the costs of electricity could fall from 70 €/MWh in 2015 to 36 €/MWh in 2050 with interconnection, and to 41 €/MWh without interconnection in the Best Policy Scenarios by 2050. Whereas, the levelised cost of electricity without greenhouse emission costs in the Current Policy Scenario is 70 €/MWh. Results of the optimisation indicate that a fully renewables based power system is the least-cost, least-GHG emitting and most job-rich option for West Africa. This study is the first of its kind study for the West African power sector from a long-term perspective.

1. Introduction

Energy crisis and susceptibility to climate change are foreseen to constrain the future human and economic growth of West African (WA) countries [1]. Globally, the need for harmonised efforts to alleviate the danger of climate change and eradicate widespread energy poverty is apparent in the perspectives of the Paris Agreement on climate change and Sustainable Development Goal no 7 (SDG 7) [2]. In WA, a great deal of attention is directed towards the interrelated problems of energy crisis, climate change and energy security, which is characterised by growing demand, poor access to electricity and huge dependence on unsustainable biofuel [3]. In doing so, the Economic Community of West African States (ECOWAS) has adopted measure to streamline renewable energy (RE) and energy efficiency into their energy policies to tackle the predominant energy challenges in the region [4].

ECOWAS is comprised of 15 member states, and is characterised by diverse socio-economic, demographic and cultural backgrounds, each of this factor influence the region's electricity production and consumption [5]. ECOWAS with a growing population above 300 million, accounts for almost one-third of Sub-Saharan Africa's population, occupying an area of over five million square kilometres [6]. The regional gross domestic product (GDP) rebounded, averaging about 2.5% in 2017 from 0.5% in 2016, and is expected to increase to 3.9% in 2019 [7]. In spite of the region's abundant energy potential and progress achieved in the establishment of the regional power pool, the West African Power Pool (WAPP) [8], the region's electricity sector is underpowered with inadequate generation and transmission systems [9], leaving about 175 million people (48%) in the region unelectrified in 2016. Further, the total population relying on biomass for cooking was 263 million (75%) in 2015 [10]. Studies on energy consumption and economic growth nexus conclude that energy is a critical parameter for socio-economic development [11]. The socio-economic development of most WA countries is hampered by its underdeveloped energy sector [12]. Most ECOWAS countries rank among the poorest, having Low Human Development [5]. Access to electricity in the region is at 52%, with shortages of up to 80 h/month and yet electricity prices in WA remain among the costliest in the world, at 0.21 €/kWh, more than twice of the global average [13]. In 2016, the electrification rate was below 40% in 10 of the 15 countries, with Guinea-Bissau, Liberia, Niger and Sierra Leone occupying the

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Technical Approaches and Institutional Alignment to 100% Renewable Energy System Transition of Madeira Island—Electrification, Smart Energy and the Required Flexible Market Conditions

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Abstract: The integration of renewable energy (RE) in energy systems can be approached in many ways depending on local possibilities. Evaluating this in the limited context of islands, this paper presents a multi-energy system transition to a 100% RE share in a two-folded technical analysis. The case study of Madeira Island using the EnergyPLAN modeling tool is used to show strengths and weaknesses of, on the one hand, electrifying all transport and heating demands on an island, while remaining demands are supplied with biomass, and, on the other hand, additional smart charging, vehicle-to-grid, thermal collectors and storages, as well as electrofuel production and storages. Technical results indicate the potentials and advantages of the second approach with 50% less biomass and no curtailment at 1–3% higher costs, compared to the first one with 7% of production curtailed. The technical analysis is supported by the institutional analysis that highlights the balancing needs through additional flexibility and interaction in the energy system. For maximum flexibility, of both demand and grid, and successful implementation of 100% RE, investment incentives and dynamic tariffs are recommended entailing more dynamic consumer involvement and strategic energy planning.

Keywords: energy system analysis; modeling; multi-energy system; smart energy system; flexible demand; self-sufficiency; dynamic market

1. Introduction

Energy systems, both large and small, are transitioning towards higher shares of renewable energy (RE), such as from wind or photovoltaic (PV), in response to replacing fossil-fuel technologies in the fight against climate change [1]. A well-planned transition to 100% RE is the main objective in many places however especially islands present challenging systems but also potential lighthouses in the struggle to analyze and identify the best approach to transitioning [2]. Not only are small and/or developing islands sensitive or even vulnerable in terms of access to energy at a reasonable cost [3], but also the importance and difficulties of various European islands was recognized in research [4], as well as politically in the "Valletta Declaration", which proclaims remote European islands as favorable for innovation [5]. Despite the differences in energy-intensity, population and geography, the common main energy objective is higher RE shares and self-sufficiency—for islands and globally.

The potential of transitioning to 100% RE has been addressed on a global level by Ram et al. [6], as well as in a more detailed review by Hansen et al. [7]. Both present the trends and latest studies on 100% RE systems and how it has gained attention especially over the last few years. While some of the studies reviewed in [7] have included cross-border interaction in national energy systems, they are

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GIS-based modelling of electric-vehicle–grid integration in a 100% renewable electricity grid

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HIGHLIGHTS

- Hourly bidding simulation of 100% renewable grid with EV charging for Australia.
- Spatio-temporal optimization to find least-cost configurations using GIS data.
- 100% renewable grid (RG) without EV is possible with 143 GW capacity and 13.5 ¢/kWh.
- 100% RG under EV controlled charging achievable with 205 GW capacity and 14.7 ¢/kWh.
- 100% RG with EV charging increases electricity cost by 1710 AUD/capita annually.

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ABSTRACT

We examine the spatio-temporal interactions of widespread electric vehicle (EV) charging with a future, 100% renewable electricity system in Australia. More specifically, we use a GIS-based electricity supply-demand model simulating an hourly competitive-bidding process over an entire year. We obtain least-cost grid configurations that include both renewable energy (RE) generators and EVs, the latter under both uncontrolled and controlled charging, and adoption rates between 0 and 100%. We characterise the vehicle-to-grid interaction in terms of overall installed capacity, hourly generation and spillage, levelized cost of electricity (LCOE), as well as transmission network expansion topology. We show that supplying 100% renewable electricity to cover current electricity needs in Australia, as well as powering all Australian passenger vehicles as controlled-charged EVs, requires 205 GW of installed capacity at an LCOE of 14.7 AUD¢/kWh. This 100% RE supply with EV charging leads to an additional electricity cost of 1710 AUD/capita annually, comparing to the current annual expenditure for electricity and conventional vehicle fuel.

1. Introduction

In the IPCC's special report on climate change, increasing the generation of electricity from renewable energy (RE) resources along with rapidly declining the carbon-intensive end-user sectors are essential to its 1.5 °C mitigation pathways [1]. The transportation sector, accounting for 28% of global final energy supply, 23% of world energy-related CO_2 emissions [2] and 65% of global oil consumption [3], features prominently in deep-decarbonization mitigation pathways. Replacing gasoline and diesel cars by electric vehicles (EVs) provides a potential solution for CO_2 emission reduction and transportation decarbonization [4].

However, due to the variability of wind and solar resources, the massive adoption of RE sources in electricity generation poses challenges in balancing generation, demand, storage, and transmission. Low wind and solar resource periods require installed capacity of renewable grids to be 3–5 times the demand, leading to significant capital cost [5]. Because their demand occurs during peak hours, EVs have the potential to exacerbate these challenges further, especially when their charging is unconstrained [6]. It is therefore necessary to investigate which configurations of energy carriers and generator sites would allow integrating large numbers of EVs under different charging strategies, and how reliable and cost-effective these configurations would be.

Most of the existing studies examining the impact of EV charging on power grids mainly focus on small virtual distribution networks or microgrids/energy hubs by considering a limited number of EVs (e.g.,

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Jordan toward a 100% renewable electricity system

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ABSTRACT

Jordan has faced two major energy crises during the past two decades; the disruption of Iraqi's oil in 2003 and Egyptian's natural gas in 2011. Restructuring Jordan's electricity supply system became a national necessity to secure sustainable electricity at affordable prices. In this work, a 100% renewable electricity supply scenario is constructed and compared with three other scenarios, which contain a mix of natural gas, nuclear, oil shale and renewable energy, in terms of techno-economic feasibility, security of supply, and carbon dioxide emissions. All the proposed scenarios were found to be economically feasible. The cumulative discount production costs, over the coming thirty five years under different fuel prices assumption, is less than 80 billion dollars (2010 dollar) for all proposed scenario. In the 100% renewable electricity scenario, the country needs around 10.6 GW of concentrated solar power, 4.5 GW of wind, and 25 GW of photovoltaic to meet the demand in the year 2050 which are achievable in terms of energy resources. The dispatchability problem of the renewable scenario was solved by proposing a 90 GWh storage system (43 CSP plants, 250 MW each, 8 h storage). Furthermore, import dependency and CO_2 emission will entirely disappear by 2050 in the renewable scenario.

1. Introduction

Environmental concerns besides securing energy supply at affordable prices demanded many countries to seek for more sustainable energy resources, such as renewable energy. Jordan has an urgent need to move toward renewable energy. The kingdom has no domestic oil or natural gas resources. It imports more than 96% of its energy demand. The energy bill has annually drained more than 10% of the national GDP during the past decade. Moreover, the disruption of the natural gas imports in 2011 has raised the kingdom energy bill up to $4.8 billion, representing 20% of the country's GDP [1]. The kingdom aims at integrating renewables into the energy mix with a share of 10% by 2020 [1]. The renewable energy and energy efficiency law, the legislative framework of renewable energy projects in the country, had been approved in 2010. Since then, many obstacles have faced the sector, and thus large renewable energy projects did not emerge into the power system until 2015. After that, Jordan's renewable energy market has been rapidly growing. The capacity of new projects under different phases around 670 MW Photovoltaic and 407 MW wind [2].

Energy planning has risen as a national necessity during the last third of the twentieth century. Many countries have designed an appropriate energy plan using different methods of planning. Rad [3] shows how energy planning has transformed from conventional methods, which analyze energy system as a demand-supply system from a techno-economic point of view, to more sophisticated methods that surround all sustainability aspects in integrated approaches. Specifying the goals of an energy plan should be followed by gathering, analyzing, and evaluating data and information. Then, developing scenarios for a future energy system and proposing an energy plan, which varies through countries and regions. Also, revision and evaluation of the energy plan should be done on a continuous basis [4].

Many energy models have been recently developed and computerized to support the planning process. Every model has a specific purpose such as policy assessment, environmental impact or matching demand and supply. More than one model could be used to achieve a more holistic plan. Rath-Nagel et al. [5] stated that “the complexity of energy policy and energy strategy issues no model can give answers to all the questions. Rather, it will require several models with different objectives and specifications in order to effectively support the development of energy policies and energy planning”.

In this work, Long-range Energy Alternatives Planning system

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On the road to 100% renewable energy systems in isolated islands

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A B S T R A C T

The integration of renewable energy sources (RES) in islands is crucial to improve their economy allowing them to be energy independent. However, the intermittency of some RES originates grid stability problems and the mismatch between demand and supply. These issues must be carefully addressed according to each island's peculiarities. The connection between isolated power systems can decrease the RES variability and, thereby, minimize the problems associated with their intermittency. Furthermore, linking all fossil fuel consuming sectors can help to shift demand and supply according to the system's requirements, following a smart energy system approach. This approach is rarely considered in studies on 100% RES in islands, as most of them only consider the power sector. The scientific contribution of this study is the assessment of the impact of the interconnection of two small islands in the path to 100% RES of the whole energy system. The EnergyPLAN model is used, and the Islands of Pico and Faial, in Azores, are the case studies considered. Although these islands can increase significantly their RES penetration with lower costs, only their interconnection allows for a complete elimination of fossil fuels' use in both islands.

1. Introduction

The use of renewable energy sources (RES) as a replacement of fossil-based fuels has been a highly discussed topic for the past years and islands are unique laboratories for the transition to a low carbon future [1].

RES integration in islands presents both opportunities and constraints. Islands are usually very dependent on imported, expensive, fossil fuels to satisfy all their energy needs [2]. Hence island's inhabitants are dependent on outside nations to guarantee their energy security and vulnerable to its pricing oscillations. Using the islands' frequently abundant endogenous resources as energy sources could tackle both these issues. Nonetheless, RES integration in isolated energy systems brings forward some difficulties related to most RES intermittent nature. Grid stability problems and mismatch between demand and supply become more crucial as RES integration share increases. More specifically, for example, solar and wind power have their largest disadvantage in their strong weather dependence. Since solar irradiation and wind speed can have sudden and large changes, the power output of a PV panel or a wind turbine can have large fluctuations, with significant impact on the operation of the power system and on the power quality. This impact increases with the increase of intermittent RES power penetration. The impact on power quality is primarily on the level and fluctuations of voltage and frequency. The system must ensure the stability of voltage and frequency within required limits. The variations in the intermittent RES power production can also cause disturbances between the power generation and power demand that can lead to dangerous operating conditions [3]. To avoid problems that can affect the safety and stability of the power supply system, intermittent RES power has to be limited to a specific percentage of the system's load [3] and non-intermittent RES power (as biomass) and energy storage must be used.

In order to achieve the objective of a 100% RES energy system, all fuel consuming sectors have to be addressed: the electricity sector has to fully eliminate power generation from fossil fuel-fired units and replace it with RES generation capacity; the transport sector has to replace its current fleet running on internal combustion engines for either battery electrical vehicles (BEVs), vehicles running on biofuels, or a combination of the two. In addition, BEVs can have the capability to deliver power from the vehicle to the grid (V2G technology). This technology is one of the many energy storage technologies that may be a part of making a flexible energy system that can better use intermittent RES [4].

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Article

Impacts of Green New Deal Energy Plans on Grid Stability, Costs, Jobs, Health, and Climate in 143 Countries

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SCIENCE FOR SOCIETY The Earth is approaching 1.5°C global warming, air pollution kills over 7 million people yearly, and limited fossil fuel resources portend social instability. Rapid solutions are needed. We provide Green New Deal roadmaps for all three problems for 143 countries, representing 99.7% of world's CO_2 emissions. The roadmaps call for countries to move all energy to 100% clean, renewable wind-water-solar (WWS) energy, efficiency, and storage no later than 2050 with at least 80% by 2030. We find that countries and regions avoid blackouts despite WWS variability. Worldwide, WWS reduces energy needs by 57.1%, energy costs from \$17.7 to \$6.8 trillion/year (61%), and social (private plus health plus climate) costs from \$76.1 to \$6.8 trillion/year (91%) at a capital cost of ~\$73 trillion. WWS creates 28.6 million more long-term, full-time jobs than are lost and needs only 0.17% and 0.48% of land for footprint and space, respectively. Thus, WWS needs less energy, costs less, and creates more jobs than current energy.

SUMMARY

Global warming, air pollution, and energy insecurity are three of the greatest problems facing humanity. To address these problems, we develop Green New Deal energy roadmaps for 143 countries. The roadmaps call for a 100% transition of all-purpose business-as-usual (BAU) energy to wind-water-solar (WWS) energy, efficiency, and storage by 2050 with at least 80% by 2030. Our studies on grid stability find that the countries, grouped into 24 regions, can match demand exactly from 2050 to 2052 with 100% WWS supply and storage. We also derive new cost metrics. Worldwide, WWS energy reduces end-use energy by 57.1%, aggregate private energy costs from \$17.7 to \$6.8 trillion/year (61%), and aggregate social (private plus health plus climate) costs from \$76.1 to \$6.8 trillion/year (91%) at a present value capital cost of ~\$73 trillion. WWS energy creates 28.6 million more long-term, full-time jobs than BAU energy and needs only ~0.17% and ~0.48% of land for new footprint and spacing, respectively. Thus, WWS requires less energy, costs less, and creates more jobs than does BAU.

INTRODUCTION

The world is beginning to transition to clean, renewable energy for all energy purposes. However, to avoid 1.5°C global warming, we must stop at least 80% of all energy and non-energy fossil fuels and biofuel emissions by 2030[1] and stop 100% no later than 2050.[1,2] Air pollution from these same sources kills 4–9 million people each year (Figure 1),[3] and this damage will continue unless the sources of air pollution are eliminated. Finally, if the use of fossil fuels is not curtailed rapidly, rising demand for increasingly scarce fossil energy will lead to economic, social, and political instability, enhancing international conflict.[3,4]

In an effort to solve these problems, studies among at least 11 independent research groups have found that transitioning to 100% renewable energy in one or all energy sectors, while keeping the electricity and/or heat grids stable at a reasonable cost, is possible.[1,5–26] The reviews of Brown et al.[27] and Diesendorf and Elliston[28] further find that critiques of 100% renewable systems are misplaced. The latter study, for example, concludes, "the main critiques published in scholarly articles and books contain factual errors, questionable assumptions, important omissions, internal inconsistencies, exaggerations of limitations and irrelevant arguments."

Among the studies that find that 100% renewable energy is cost effective, many have been of limited use to policy makers because they considered only private cost and not social cost, did not compare business-as-usual (BAU) with wind-water-solar

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Solar driven net zero emission electricity supply with negligible carbon cost: Israel as a case study for Sun Belt countries

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ABSTRACT

A high temporal and spatial resolution energy transition study was performed using a linear optimization based energy system transition model. The study uses Israel's electricity sector dataset, which has important characteristics typical for several Sun Belt countries. It has 7 scenarios aimed at assessing the impacts of various policy factors, such as carbon cost and coupling to the water sector. Under the present renewable electricity technology cost projections, a carbon cost only speeds up the transitions into renewable electricity. However, a No Carbon Cost scenario also achieves comparable results by 2050 (with only 2% fossil). The levelized cost of electricity in 2050 was shown to be less than that of 2015 in all scenarios except under the Current Policy. The Current Policy scenario will significantly increase the cost of electricity in the post-2020 period even when a carbon cost is ignored. The observed emission reduction comes after 2030 but there are still significant emissions by 2050. This shows that Israel's present energy policy carries multiple risks to the nation. Alternatively, Sun Belt countries, such as Israel, can speed the transition of the electricity sector without the need to implement carbon cost, only by promoting solar photovoltaics and supporting batteries.

1. Introduction

Transitioning to a net zero greenhouse gas (GHG) emission energy system by 2100 is the only option to avoid a global temperature increase of 2 °C compared to the preindustrial level. The 2015 United Nations Climate Change Conference, COP21, outcome has produced an agreement to reduce carbon emissions of 196 participating countries [1]. The agreement gives countries the responsibility to set their own nationally determined target. However, even though the target of the Paris Agreement is based on science, the lack of expected ambitious goals in several (Intended) Nationally Determined Commitments ((I)NDC) of countries shows a significant difference with the science based target [2]. According to a study by Rogelj et al. [3], if climate action continues at the same rate of reduction as seen in the present INDC submitted by countries, the temperature will be higher than the target set in the Paris Agreement, which aims for a global temperature increase well below 2 °C, with an effort to limit it to 1.5 °C. It is impossible to achieve the targets of the Paris Agreement without achieving a net zero emission energy system well before the year 2100. As a result, some studies have shown the need for an aggressive investment in Renewable Energy (RE) technology in some countries [4], such as India, China and USA. While others studied the global [5] need to increase RE to meet the aspired target. This requires an improved policy [6]. This paper presents case studies that will clarify the gap in policymaking as well as the associated risk together with the alternative solution.

Currently, researchers and investors see RE as a comparably low risk area, leaving the risk mostly to policy changes of any kind. Consequently, RE technologies are set to continue its remarkable growth. The projected massive PV capacity growth is expected to result in cost reduction [7], which improves its cost competitiveness [8] and the ability to revolutionize the energy system [9]. Agreement on the promising future of PV technology is common even if the magnitude of cost reduction seen at global level [10] differs from the one expected at a particular location on the globe [11]. Possible cost reduction for PV and wind energy [12] as well as batteries [13] are also reported. These are one of the many reasons that improves RE technology competitiveness [14] and world RE perspective [15]. Perspectives on the RE technology role in the future global energy outlook [16] and the levelized cost of its electricity [17] are also improving year to year. Several researchers

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Pathway towards achieving 100% renewable electricity by 2050 for South Africa

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ABSTRACT

Transition to a cost effective and fossil carbon-free energy system is imminent for South Africa, so is the mitigation of issues associated with the 'water-energy nexus' and their consequent impacts on the climate. The country's key fossil carbon mitigation option lies in the energy sector, especially in shifting away from the coal-dependent power system. Pathways towards a fully decarbonised and least cost electricity system are investigated for South Africa. The energy transition is simulated for five scenarios, assessing the impact of various factors such as sector coupling, with and without greenhouse gas (GHG) emission costs. South Africa's energy transition is simulated using an hourly resolved model until 2050. This modelling approach synthesises and reflects in-depth insights of how the demand from the power sector can be met. The optimisation for each 5-year time period is carried out based on assumed costs and technological status until 2050. The modelling outcomes reveal that solar PV and wind energy, supplying about 71% and 28% of the demand respectively in the Best Policy Scenario for 2050, can overcome coal dependency of the power sector. The levelised cost of electricity increases just slightly from 49.2 €/MWh in 2015 to 50.8 €/MWh in the Best Policy Scenario, whereas it increases significantly to 104.9 €/MWh in the Current Policy Scenario by 2050. Further, without considering GHG emissions costs, the cost of electricity slightly increases from 44.1 €/MWh in 2015 to 47.1 €/MWh in the Best Policy Scenario and increases up to 62.8 €/MWh in the Current Policy Scenario by 2050. The cost of electricity is 25% lower in the Best Policy Scenario than in the Current Policy Scenario without factoring in GHG emissions costs and further declined to 50% with GHG emissions costs. The Best Policy Scenario without GHG emissions costs led to 96% renewables and the remaining 4% is supplied by coal and gas turbines, indicating pure market economics. The results indicate that a 100% renewable energy system is the least-cost, least-water intensive, least-GHG-emitting and most job-rich option for the South African energy system in the mid-term future. No new coal and nuclear power plants are installed in the least-cost pathway, and existing fossil fuel capacities are phased out based on their technical lifetime.

1. Introduction

South Africa is the fifth most populated country in Africa, with a population of 56.7 million in 2017 and an annual average population growth rate of 1.2%, occupying an area of 1.219 million km^2 (World Bank, 2017). The country's GDP is 349b€ with a growth rate of 1.3% in 2017 (World Bank, 2017). The electricity demand is expected to increase from 245 TWh in 2015 to 522 TWh in 2050, with an annual average growth rate of 2.3% (Wright et al., 2017). South Africa, like any other coal-abundant country, is susceptible to huge environmental crises, due to over-reliance on coal-generated electricity (Baker and Sovacool, 2017; Klausbrucker, 2016). Coal-fired power plants account for over 90% of electricity production in South Africa (Menyah and Wolde-Rufael, 2010). The country is listed amongst the world's most fossil carbon-intensive economies and is ranked as the 7th largest emitter of greenhouse gas (GHG) per capita (Alton et al., 2014). In Africa, South Africa remains the largest CO_2 emitter and accounts for 42% of the continent's emissions (Alton et al., 2014). South Africa commits, as defined in national policy, a peak, plateau and decline GHG emissions trajectory range, with emissions by 2025 and 2030 in a range of between 398 and 614 Mt_{CO2eq}, as per the 2015 intended nationally determined contribution (DEA, 2015). The country's main fossil carbon mitigation option lies in shifting away from its coal dependence in the power sector (DEA, 2015), which complies with the Paris Agreement on

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Full energy system transition towards 100% renewable energy in Germany in 2050

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ABSTRACT

Germany has set ambitious policies for increasing renewable energy shares and decommissioning nuclear energy, but there are certain scientific gaps on how this transition should occur, especially when considering all energy sectors. The purpose of this study is to advance the knowledge of transitioning the German energy system to 100% renewable energy towards 2050. Taking into consideration renewable resource potentials, energy system costs and primary energy supply this study develops a path for transitioning the German energy system within the heating, industrial, transport and electricity sectors. The analysis demonstrates that it is possible to carry out this transition from a technical and economic perspective with some measures being vital for achieving this ambition in a cost-effective manner. The most significant challenge in this transition is regarding resource potentials where especially biomass resources are constrained and under pressure. Finally, the most influential measures for achieving the renewable transition are discussed.

1. Introduction

In the past years, ambitious climate policies have been agreed such as for the German energy transition (Energiewende) in the early 2010's and the Paris agreement in 2015 for reducing the CO_2-emissions and global temperature increase [1,2]. The challenge is how to achieve these targets while also considering other factors such as costs of energy, resource availability and cross-country collaborations. This paper addresses the German energy transition by developing a strategy for achieving 100% renewable energy in the entire energy system.

The Energiewende was formed in the early 2010's, based on decades of energy policy discussions in Germany affected by numerous events and key drivers leading to ambitious climate targets and a phase-out of nuclear power [3]. It is crucial to understand that it has been a long process, which highlights the importance of long-term planning in the energy sector with complex infrastructure [4]. The Energiewende targets aim at reducing the greenhouse gas emissions by 80–95% in 2050 compared to 1990 while increasing the renewable share of final energy to at least 60% and the renewable share of electricity demands to 80%. In addition, targets are stated for reducing primary energy demands, as well as for electricity, heat and transport demands [5].

Previous solutions for the German energy transition have focused on the Energiewende policy development and less on the actual energy infrastructure design to achieve the emission targets. Examples show that policies are key in determining the future energy development [4] and that the current legislation does not support a transition towards the Energiewende targets, especially when focusing on the current and future heating market [6]. Several studies focus on the implementation of the Energiewende by regional implementation of renewable energy in Germany [7] or on how wind power auctions should be designed in the future [8]. Other studies discuss the importance of including institutions and actors in defining the future system simultaneously with introducing technologies to the energy system [9].

Numerous studies focus on individual sectors within the energy system such as transportation and electric vehicles [10–12], the heating market [6] or the future development in the German electricity market given the current policies [13]. Schmid et al. [14] provides a review of five studies for achieving the Energiewende in Germany, but primarily within the electricity sector and excludes other energy sectors. Similarly, Lehmann and Nowakowski focus on the electricity sector by analyzing three different scenarios for structuring the future renewable electricity sector [15]. These scenarios focus on a decentralized, a centralized and a pan-European approach for integrating further renewables. Along these lines, Gullberg et al. [16] evaluate benefits of a stronger connection between the Norwegian and German energy systems in order to use the Norwegian hydropower capacities as reserves for storing electricity. Other technical challenges are defined qualitatively in [17] by highlighting which bottlenecks need to be overcome

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Integration of transport and energy sectors in island communities with 100% intermittent renewable energy sources

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ABSTRACT

Islands' energy systems present a challenge in energy planning due to a limited amount of resources which could be used to make islands self-sufficient and sustainable. This paper presents a novel approach for defining energy system of a carbon neutral island which utilizes only intermittent renewable energy sources in combination with vehicle-to-grid concept as a demand response technology, where marine transportation has also been taken into account. Integration of power, heating, cooling and transport sectors has been modelled by using EnergyPLAN tool, i.e. its updated November 2017 version which is capable of simulating vehicle-to-grid operation in mentioned conditions. Power supply capacities have been selected not by using scenario analysis but by implementing an optimization procedure based on series of simulations in EnergyPLAN tool. In order to choose the most suitable power supply system configuration, two boundary conditions have been defined. Firstly, only solar and wind capacities must be utilized. Secondly, total electricity import and export must be balanced, i.e. the island has to be CO_2 neutral. In order to validate the approach, Croatian Island of Korčula has been used as the case study. 2011 has been selected as the base year for which final energy consumption has been calculated. The final simulation year was set to 2030 in which optimal capacities are installed. It has been shown that configuration with 40 MW of wind and 6 MW of installed solar capacities presents the least cost solution, while 22 MW of wind in combination with 30 MW of installed solar capacities provides the lowest amount of total electricity import and export. Analysis of the vehicle-to-grid share reduction has shown increase in total import and export in both cases, while transmission peak loads have not been influenced.

1. Introduction

A large majority of island communities are traditionally experiencing difficulties in terms of energy supply and energy security associated with a high dependency on imported fossil fuels. Growing concerns about climate change and increasing profitability of renewable based energy technologies contribute to higher shares of the renewable energy source (RES) utilization on a number of islands. Lately, a step forward in the endeavour to achieve energy self-sufficient islands has become integration of power sector with energy demand of domestic heating, cooling, fuels for transport or larger, commercial demand.

On the one hand, islands have a significantly unexploited potential for sustainable development while on the other, they are among the most vulnerable areas to experience a variety of impacts of climate change on their local ecosystem and livelihoods. Both have been recognised and acknowledged by several initiatives targeting sustainable development on islands. The International Renewable Energy Agency actively supports small island developing states (SIDS) into their renewable energy transition since 2011 [1] and coordinates the worldwide SIDS Lighthouse Initiative launched at the 2014 Climate Summit [2]. The SIDS Initiative supports energy transformation on islands from fossil-fuel based power systems enabling smart deployment of renewable energy in power, heating, cooling and transportation sectors. The European Union (EU) developed two strategies to treat climate change and sustainable development on islands under the same umbrella, namely Clean Energy for EU Islands [3] and Smart Island Initiative [4]. The latter represents a bottom-up initiative tackling climate change and supporting sustainable economic growth through a holistic approach by exploiting synergies between sectors, thus directly addressing the circular economy. Initiatives seek to gather European islands by developing a common method for the clean energy transition focusing on smart islands principles. Some researchers are also developing tools

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Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe

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ABSTRACT

Two transition pathways towards a 100% renewable energy (RE) power sector by 2050 are simulated for Europe using the LUT Energy System Transition model. The first is a Regions scenario, whereby regions are modelled independently, and the second is an Area scenario, which has transmission interconnections between regions. Modelling is performed in hourly resolution for 5-year time intervals, from 2015 to 2050, and considers current capacities and ages of power plants, as well as projected increases in future electricity demands. Results of the optimisation suggest that the levelised cost of electricity could fall from the current 69 €/MWh to 56 €/MWh in the Regions scenario and 51 €/MWh in the Area scenario through the adoption of low cost, flexible RE generation and energy storage. Further savings can result from increasing transmission interconnections by a factor of approximately four. This suggests that there is merit in further development of a European Energy Union, one that provides clear governance at a European level, but allows for development that is appropriate for regional contexts. This is the essence of a SuperSmart approach. A 100% RE energy system for Europe is economically competitive, technologically feasible, and consistent with targets of the Paris Agreement.

1. Introduction

The European Commission has adopted a framework strategy to establish an Energy Union that aims to assist in the transition towards greater sustainability, energy security and economic competitiveness [1]. The union aims to build greater solidarity and cooperation amongst Member States in order to pool and diversify energy resources. This would include integrating energy markets, and strengthening transmission interconnections where necessary to “make the European Union (EU) the world number one in renewable energy and lead the fight against global warming” [1]. In July, 2018 the trio of France, Spain and Portugal agreed that there would be a strategic role of interconnections to add value in Europe, to honour commitments related to the Paris Agreement, and to promote convergence between Member States [2]. Concurrently, the European Commission proposes to support efforts involving cross-border renewable energy (RE) projects, and continue to promote key trans-European network infrastructures [3].

Two relevant issues have emerged related to governance of the Energy Union. The first concerns the overall objective and timeframe of the union. Some argued that in order to achieve the goals of the Paris Agreement, a “red line” of achieving net-zero greenhouse gas (GHG) emissions by 2050 was needed to avoid liabilities for future generations [4]. At the same time, some Member States displayed reluctance to mention a specific date. Ultimately, the final wording agreed upon was to aim for net-zero GHG emissions “as early as possible”, but it appears that future scenarios and decarbonisation plans for the EU and its Member States will need to show how the objective of net-zero by 2050 could be achieved. The latest long-term vision for Europe incorporates this objective [5] and warns that not achieving such a goal could be a major threat to security and prosperity.

The second issue concerns the level of interconnection that would be needed to achieve such goals. Lilliestam and Hangar [6] describe the contrasting views of two organisations that advocate 100% renewable energy futures for Europe, EUROSOLAR [7] and DESERTEC [8]. On the one hand, EUROSOLAR advocates decentralisation of energy and the disempowerment of the actors and structures that have produced an unsustainable and undemocratic energy system [9]. On the other hand, DESERTEC envisions a highly centralised and regulated system of imports and exports of solar

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A cost optimal resolution for Sub-Saharan Africa powered by 100% renewables in 2030

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ABSTRACT

This paper determines a least cost electricity solution for Sub-Saharan Africa (SSA). The power system discussed in this study is hourly resolved and based on 100% Renewable Energy (RE) technologies. Sub-Saharan Africa was subdivided into 16 sub-regions. Four different scenarios were considered involving the setup of a high voltage direct current (HVDC) transmission grid. An integrated scenario that considers water desalination and industrial gas production was also analyzed. This study reveals that RE is sufficient to cover 866.4 TWh estimated electricity demand for 2030 and additional electricity needed to fulfill 319 million m^3 of water desalination and 268 TWh_{LHV} of synthetic natural gas demand. Existing hydro dams can be used as virtual batteries for solar PV and wind electricity storage, diminishing the role of other storage technologies. The results for total levelised cost of electricity (LCOE) decreases from 57.8 €/MWh for a highly decentralized to 54.7 €/MWh for a more centralized grid scenario. For the integrated scenario, including water desalination and synthetic natural gas demand, the levelised cost of gas and the levelised cost of water are 113.7 €/MWh_{LHV} and 1.39 €/m^3, respectively. A reduction of 6% in total cost and 19% in electricity generation was realized as a result of integrating desalination and power-to-gas sectors into the system. A review of studies on the energy future of Sub-Saharan Africa provides the basis for a detailed discussion of the new results presented.

1. Introduction

The need for a revolution in the energy sector globally is vital, in view of tackling the problems of global warming, pollution, climate change, and energy security. The usage of and further dependence on fossil fuels in the pursuit of energy generation will engender an increase of greenhouse gas emissions and more extreme climate impacts. The energy sector accounts for roughly two-third of all anthropogenic greenhouse gas emissions, and there is imminent need for a paradigm shift from conventional to renewable energy resources that are sustainable, clean and cost effective [39,52,57]. Investment in sustainable energy infrastructure is a crucial link between economic growth, development, and climatic action. Renewable electricity generation will ensure the reduction of carbon dioxide emissions and meet climatic targets. A renewable energy optimization solution will reduce the dependency on fossil fuels as the predominant energy sources in the power system, and address socio-economic development needs and vulnerability to environmental change [23,46].

The region of Sub-Saharan Africa (SSA) continues to face significant energy crises. Despite the unique potential of energy sources in the region, a severe energy shortage has yet to be conquered, and access to electricity eludes millions of people [48]. Billions of dollars are spent annually on inefficient and often dangerous alternatives such as kerosene lamps, candles, flashlights, or other fossil-fueled powered stopgap technologies. In 2012 almost 16 TWh of electricity demand was served by backup generators for service and industrial activities in SSA [48,8]. The current energy challenge in Africa requires a rapid increase in energy supply (growth and development of energy) for the continent due to growing population, unprecedented economic progress and a need for reliable, modern energy services. Supply of energy is expected to at least double by 2030 and might even triple for electricity [56].

Africa's electricity generation varies significantly among African countries. North Africa (more than 99% electricity access) dominates in terms of electricity generation from a continental perspective [58], while Sub-Saharan Africa is starved for electricity. Only seven countries, Cameroon, Côte d'Ivoire, Gabon, Ghana, Namibia, Senegal and South Africa have electricity access rates exceeding 50%. The average annual consumption in Sub-Saharan Africa (except South Africa) is only about 150 kWh/capita [20]. Electricity demand in Africa was 385 TWh and 621 TWh in 2000 and 2012, respectively, and estimated to increase to about 1258 TWh and 1869 TWh by 2030 and 2040, respectively. The Sub-Saharan African demand will be about 812 TWh and 1297 TWh by

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Radical transformation pathway towards sustainable electricity via evolutionary steps

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A transition towards long-term sustainability in global energy systems based on renewable energy resources can mitigate several growing threats to human society simultaneously: greenhouse gas emissions, human-induced climate deviations, and the exceeding of critical planetary boundaries. However, the optimal structure of future systems and potential transition pathways are still open questions. This research describes a global, 100% renewable electricity system, which can be achieved by 2050, and the steps required to enable a realistic transition that prevents societal disruption. Modelling results show that a carbon neutral electricity system can be built in all regions of the world in an economically feasible manner. This radical transformation will require steady but evolutionary changes for the next 35 years, and will lead to sustainable and affordable power supply globally.

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Analysing the feasibility of powering the Americas with renewable energy and inter-regional grid interconnections by 2030

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ABSTRACT

The Sustainable Development Goals and the Paris Agreement, as the two biggest climate action initiatives, address the need to shift towards a fully sustainable energy system. The deployment of renewable energy, especially solar and wind power, decreases carbon dioxide emissions, but presents issues of resource intermittency. In this study, a cost-optimised 100% renewable energy based system is analysed and quantified for the Americas for the reference year 2030 using high spatially and temporally resolved weather data. Several scenarios have been applied, from a decentralised power system towards a fully centralised and interconnected system, taking into account a mix of renewable energy, energy storage and transmission networks. This research aims to evaluate the benefits of an interconnected energy system for the Americas. The levelised cost of electricity (LCOE) is between 48.8 and 59.0 €/MWh depending on the chosen scenario. The results show that the LCOE and total annualised cost drop by 14% and 15%, respectively, in a centralised power system. The optimised utilisation of transmission grids leads to less energy storage requirement. Sector coupling brings further benefits by reducing additional 4% of LCOE, where electricity demand for power, seawater desalination and non-energetic industrial gas sectors have been supplied. A comparison between the interconnected Americas and North and South America individually shows a reduction of 1.6% and 4.0% for the total annual system cost and LCOE. Although the cost of the energy system decreased due to wide grid interconnection, substantial benefits have not been achieved as reported earlier for a Pan-American energy system. A scenario with synthetic natural gas (SNG) trading through a liquefied natural gas value chain has also been presented. The results suggest that local SNG production cost in the assumed consumption centre is almost the same as the cost of imported SNG.

1. Introduction

Ensuring access to affordable, reliable, and sustainable energy for all people, specified by the United Nations' Sustainable Development Goals (SDGs) [1] for 2030, necessitates transcendent changes in the energy sector globally. The Paris Agreement [2] is another important climate action target agreed on during the COP21 (2015 United Nations Climate Change Conference) in Paris in 2015. These global initiatives highlight the urgent need for a change away from the current energy system towards a fully sustainable energy system. Putting these two crucial agreements into action will undoubtedly help to accelerate the goal of restricting the global temperature increase to 1.5–2 °C above pre-industrial levels.

The global population is projected to increase, spurred on by increasing populations in developing countries. Similarly, the global demand for energy will increase, creating more challenges for suppliers and distributors to provide affordable and reliable energy for all. Natural resources and traditional biomass fuels for cooking are still the main sources of energy in most countries worldwide. However, these sources do not fit in the SDGs, mainly because they are limited and involved in high levels of greenhouse gas (GHG) emissions production. Therefore, the adoption of alternative energy sources makes increasingly more sense these days. Renewable energy (RE) sources, in particular solar and wind, are the most promising sources of energy to substitute fossil fuels [3–5]. As the cost of RE decreases rapidly, the interest to develop these sources of energy increases.

Increasing RE share in the primary energy generation raise the need for very strong electric grids on a national level and beyond. This can be explained by the fact that RE sources are not evenly distributed and not constantly available throughout the year. Variability of RE can be managed through different ways, such as sector coupling, national and international transmission grid interconnection, supply- and demand-

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Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes

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ABSTRACT

Matching electricity, heat, and cold demand with supply at low cost is the greatest concern facing countries seeking to provide their all-purpose energy with 100% clean, renewable wind, water, and sunlight (WWS). Implementing WWS worldwide could eliminate 4–7 million annual air pollution deaths, first slow then reverse global warming, and provide energy sustainably. This study derives zero-load-loss technical solutions to matching demand with 100% WWS supply; heat, cold, and electricity storage; hydrogen production; assumed all-distance transmission; and demand response for 20 world regions encompassing 139 countries after they electrify or provide direct heat for all energy in 2050. Multiple solutions are found, including those with batteries and heat pumps but zero added hydropower turbines and zero thermal energy storage. Whereas WWS and Business-As-Usual (BAU) energy costs per unit energy are similar, WWS requires ~42.5% less energy in a base case and ~57.9% less in a heat-pump case so may reduce capital and consumer costs significantly. Further, WWS social (energy + health + climate) costs per unit energy are one-fourth BAU's. By reducing water vapor, the wind turbines proposed may rapidly offset ~3% global warming while also displacing fossil-fuel emissions. Thus, with careful planning, the world's energy challenges may be solvable with a practical technique.

1. Introduction

Globally averaged temperatures in 2016 were over 1 °C higher than at the end of the 19th century [1]. To avoid 1.5 °C warming and eliminate the 4–7 million worldwide premature air pollution deaths occurring annually, the world must rapidly replace fossil fuels with zero-emissions energy sources. To help accomplish this goal, 139 individual country roadmaps were recently developed to transition all energy sectors (electricity, transportation, heating/cooling, industry, and agriculture/forestry/fishing) to use electricity and direct heat powered by 100% wind, water, and sunlight (WWS) by 2050, with 80% conversion by 2030 [2]. Only WWS technologies were used in that study, as they provide greater air pollution health and climate benefits than do bioenergy or fossil fuels with carbon capture and sequestration (CCS) [3]; use less land than crop-based bioenergy [3]; and result in less catastrophic risk, weapons proliferation risk, waste, and delays than nuclear power [3,4].

Whereas, the 139-country roadmaps estimate the numbers of WWS generators needed for each country to match annually-averaged electricity, heat, and cold power demand with WWS supply, they do not provide a detailed analysis of matching supply with demand over shorter time scales (e.g., minutes, hours, months, or seasons). Such an analysis is necessary, as the concern for load loss (supply shortfall) due to the variability of WWS resources and associated costs of mitigating such uncertainty is the greatest barrier facing the large-scale, worldwide adoption of WWS power [5].

Previous advanced studies have examined matching time-dependent demand with supply for up to 100% renewable energy by replacing conventional generators with WWS, or WWS plus bioenergy in either the electric power sector alone, or in the electric sector plus one or two other sectors after they have been electrified

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Article

The Impacts of High V2G Participation in a 100% Renewable Åland Energy System

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Abstract: A 100% renewable energy (RE) scenario featuring high participation in vehicle-to-grid (V2G) services was developed for the Åland islands for 2030 using the EnergyPLAN modelling tool. Hourly data was analysed to determine the roles of various energy storage solutions, notably V2G connections that extended into electric boat batteries. Two weeks of interest (max/min RE) generation were studied in detail to determine the roles of energy storage solutions. Participation in V2G connections facilitated high shares of variable RE on a daily and weekly basis. In a Sustainable Mobility scenario, high participation in V2G (2750 MWh_e) resulted in less gas storage (1200 MWh_{th}), electrolyser capacity (6.1 MW_e), methanation capacity (3.9 MWh_{gas}), and offshore wind power capacity (55 MW_e) than other scenarios that featured lower V2G participation. Consequently, total annualised costs were lower (225 M€/a). The influence of V2G connections on seasonal storage is an interesting result for a relatively cold, northern geographic area. A key point is that stored electricity need not only be considered as storage for future use by the grid, but V2G batteries can provide a buffer between generation of intermittent RE and its end-use. Direct consumption of intermittent RE further reduces the need for storage and generation capacities.

Keywords: energy system modelling; storage solutions; 100% renewable energy; Åland; vehicle-to-grid; power-to-gas

1. Introduction

Driven by efforts to eliminate dependency on imported fossil fuels and increase overall sustainability, island nations and regions of archipelago may encounter higher shares of renewable energy in their energy systems much faster than their continental counterparts. In doing so, these regions will be the first to determine optimal levels of various energy storage solutions needed as higher shares of intermittent renewable energy (RE) resources are assimilated [1]. Furthermore, island groups represent interesting case studies of transitions as their energy systems are relatively compact, homogeneous, and less complex. For these reasons, such regions may offer potential blueprints or test-beds for energy system transitions toward sustainability that will happen on a wider scale in the future [2].

In order to encourage a transition away from fossil fuels and toward sustainability on the Aegean Archipelago Islands, Kadellis et al. [3] suggest that island energy systems based on RE and appropriate Energy Storage Solutions (ESS) can aid in achieving both environmental goals and result in financial advantages. Further, Hlusiak et al. [4] highlight how utilising the storage potential of battery electric vehicles (BEV) can contribute to island grid stability while not imposing significant restrictions on electric vehicle range. The potential coupling of RE generation and electrified mobility, therefore, seems promising.

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Cost-optimal design of a simplified highly renewable Chinese electricity network

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ABSTRACT

Rapid economic growth in China has lead to an increasing energy demand in the country. In combination with China's emission control and clean air initiatives, it has resulted in large-scale expansion of the leading renewable energy technologies, wind and solar power. Their intermittent nature and uneven geographic distribution, however, raises the question of how to best exploit them in a future sustainable electricity system, where their combined production may very well exceed that of all other technologies. It is well known that interconnecting distant regions provides more favorable production patterns from wind and solar. On the other hand, long-distance connections challenge traditional local energy autonomy. In this paper, the advantage of interconnecting the contiguous provinces of China is quantified. To this end, two different methodologies are introduced. The first aims at gradually increasing heterogeneity, that is non-local wind and solar power production, to minimize production costs without regard to the match between production and demand. The second method optimizes the trade-off between low cost production and high utility value of the energy. In both cases, the study of a 100% renewable Chinese electricity network is based on 8 years of high-resolution hourly time series of wind and solar power generation and electricity demand for each of the provinces. From the study we conclude that compared to a baseline design of homogeneously distributed renewable capacities, a heterogeneous network not only lowers capital investments but also reduces backup dispatches from thermal units. Installing more capacity in provinces like Inner Mongolia, Jiangsu, Hainan and north-western regions, heterogeneous layouts may lower the levelized cost of electricity (LCOE) by up to 27%, and reduce backup needs by up to 64%.

1. Introduction

China is undergoing tremendous challenges of decarbonization and air quality impairment due to rapid industrial growth, transportation expansion and sharply increased demands of electricity [1]. Coal as the main source of power is being changed, and the employment of alternative sources has become an important part of the Chinese energy policy. For many years, the only renewable energy source in China has been hydro, meeting 19% of annual electricity demand in 2014 [2]. But hydro is reaching its full potential due to site limitations. Wind and solar power, however, have become affordable [3] and more suitable for large scale expansion [4–6].

Considering the growing penetration of renewables, some scholars have looked into implications of integrating large amounts of wind and solar energy in the Chinese power sector. A combined source-grid-load planning model [7] was introduced to seek a cost-optimal solution at the macro level, taking into account higher renewable penetration up to 2030. They suggested striking a balance between resource-rich and high-load regions by means of a rapid expansion of the inter-regional transmission grid. The same is suggested by Ref. [8]. In this context, economic savings and better utilization of wind and solar power may be achieved by shifting renewable capacities towards resource-rich regions that are linked to regions with high demands by high-capacity transmission lines. In the studies, emphasis was given to policy target driven scenarios and system cost reductions were not explicitly discussed.

Both [7] and [8] studied the renewable integration using annual average values. This does not explicitly capture the variable nature of renewables. Ref. [9] is the first study to base the analysis on hourly data. The high temporal resolution allowed insights into backup, storage and flexibility needs. All three studies were

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100% renewable energy system in Japan: Smoothening and ancillary services

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HIGHLIGHTS

- Hourly simulation using real atmospheric data.
- Reliability assessment of 100% renewable energy grid.
- Feasibility of the system is assured provided large-scale implementation of batteries.

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ABSTRACT

In the aftermath of the Paris Agreements, many countries around the globe have pledged to reduce the amount of greenhouse gas emissions being released into the atmosphere. To do so, it is important that the amount of renewable energy in the electricity grid increases. However, there are worries of the capacity of the grid to cope with intermittent energy sources. To assess the feasibility of a 100% renewable energy system in Japan, the authors conducted an hourly simulation of future electricity production based on wind, solar and tidal data. The system was shown to be stable, and the authors calculated the required capacity of electrical batteries that would be necessary to balance such a system.

1. Introduction

One of the most important events of recent times in Japan took place on the 11th of March 2011, when a large earthquake offshore of its northeast region created a tsunami that went on to devastate large parts of the country's coastline. The tsunami overtopped coastal defences and brought down the cooling systems at the Fukushima Dai-ichi nuclear power plan, ultimately resulting in the release of large amounts of radioactive material into the environment. As a result of this accident and other earthquake related damage, and also due to large public opposition to this source of energy [1], all nuclear reactors were shut down. The newly created Nuclear Regulation Authority (*Genshiryoku Kisei Iinkai*, NRA) began carrying out safety inspections and stress test assessments in 25 of Japan's existing nuclear power reactors, though it is unclear how many will eventually be brought back online. Public opinion, supported by district court injunctions and prohibitive retrofitting costs, are some of the major obstacles to the restart of the idle nuclear fleet.

To compensate for the offline nuclear reactors a significant amount of fossil fuel power was brought online, which resulted in increases in

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Long-term effects of 100% renewable generation on the Colombian power market

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ABSTRACT

The power industry is changing worldwide from fossil-based energies to renewables, this trend has been mainly fostered by governments seeking to reach decarbonisation. In particular, renewable energies as solar and wind pose benefits and challenges on traditional power system, e.g., they are environmentally friendly but their intermittency and seasonality is a challenge for security of supply. Though, this is not obstacle for countries to produce almost 100% of its electricity from renewables, such is the case in Costa Rica, Paraguay and Iceland. In this context, and given multiple uncertainties tied to the spread of renewable energies, this paper uses a simulation model to analyse a scenario with 100% renewable energy supply. This paper concludes that for the Colombian case, a large hydroelectric component and its complementarity with solar and wind reduce prices and increase energy efficiency, while helping security of supply.

Introduction

Renewable energy growth is transforming the electricity industry [1]. This is due to worldwide climate alerts that have prompted government agreements on strategies to reduce greenhouse gases (GHGs), thereby promoting renewable investments in the electricity industry, the largest GHG emitter [2–4]. Though, the investment in renewable energies is not only motivated by environmental reasons but also by economic reasons, as these technologies have become more cost-competitive compared with conventional energies [5,6]. As a consequence of this transformation, renewables, such as wind and solar photovoltaic (PV), are increasing with implications for energy security because of their intrinsic intermittency [7].

Investing in renewable energies such as wind and solar PV entails advantages and disadvantages to power sector. Some advantages include the low level of maintenance, limitless source of energy, and their environmental effects [8]. Some disadvantages include their lower availability factors regarding to conventional technologies, unpredictability, and their inherent variability that needs to be balanced in real-time [9–12].

As mentioned above, the intermittent generation from renewable energies needs of flexible power plants - usually based on fossil fuel - that can be called up at short notice if the wind falls or the sun fades [13]. To guarantee the availability of these flexible power plants a capacity mechanism is used, this ensures long-term security of supply by providing regular payments to capacity providers, which must be available when the system is tight [14]. Although, some countries use an energy-only market design to promote investment in new generation capacity, driven solely by electricity price [15,16]. In energy-only markets investments in new capacity may become ineffective in some cases - as wholesale electricity price may not cover the costs of generation investments [17,18].

Scholars are investigating alternative incentives to secure electricity supply under high levels of renewable energy investments [13,19,20]. These papers conclude that though, on the one hand, renewables pose challenges to electricity markets, on the other hand, it is feasible to achieve security of supply with high penetrations of renewables.

At this point, some may still argue that renewable energies need fossil fuels to become the major player in the power sector. But this is not strictly true as in the last years several places around the world have almost achieved 100% renewable power. Such is the case of Costa Rica, Paraguay, Norway and Iceland [21,22]. The aforementioned countries reached almost 100% renewable supply by dealing with: the variability of renewable energies, the power grid integration changes, the vested

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Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050

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ABSTRACT

The main aim of this study is to present an energy transition roadmap for Pakistan in which the total energy demand by 2050 is met by electricity generated via renewable sources, in particular, solar photovoltaic. Efforts have been made to assess the energy and cost required for the transition towards a sustainable energy supply covering the demand for power, desalination and industrial gas sectors. Hourly resolved model was used and optimization was carried out for each time period (transition is modeled in 5-year steps) on the basis of assumed costs and technological status till 2050 for all energy technologies involved. Solar PV dominates the installed technologies and contributes 92.7% and 96.6% in power and integrated scenarios. Seawater desalination sector dominates the integrated scenario and clean water demand is found to be $2.8 \cdot 10^{11}$ m^3 by 2050. The levelised cost of electricity declines from 106.6 €/MWh in 2015 to 46.2 €/MWh in 2050 in power scenario. In country-wide scenario, gas storage rules from 2040 to 2050 in terms of total storage capacities while battery storage is prominent in terms of storage output. The results indicates that, 100% renewable system is cost competitive and least cost option for Pakistan's future energy transition.

1. Introduction

Industrialization, intensive use of fossil fuels and nitrogenous fertilizers has pumped more greenhouse gas (GHG) into atmosphere than any natural processes could possibly have done. It is urgently crucial to reduce the carbon dioxide emissions by a significant amount [1]. The level has been estimated at 450 ppm, which would mean a global increase of 2° Celsius in mean ground temperature [2].

Pakistan with more than 188 million inhabitants stands as the sixth most populous country in the world (2013). Traditionally, Pakistan was an agrarian economy, but over the time, industry and services sector have become main contributors to the GDP [3]. Presently energy production and consumption in Pakistan basically depend on conventional fuels. Pakistan's total installed capacity breakdown for the year 2014 has been shown in Fig. 1. Oil and gas contribute 63% (gas 33.0% and oil 30.0%) to the total energy supplies [3,4]. However, the increased dependence on natural gas cannot continue owing to the rapid depletion of country's gas reserves. It has been assessed that only 25–30% of the total assets will be left by the year 2027–28 [5]. The commercial sector is the biggest consumer of energy by consuming 37.6% of total energy, while the transport, residential and commercial sectors consumed 31.4%, 23.4% and 4.0% respectively in 2013 [6,7]. Pakistan's electricity consumption has grown at a compound annual growth rate (CAGR) of 4.6% from 2000 to 2015 [8]. The growth in electricity consumption has been mainly attributed to the increase in population, economic growth, increase in income per capita and urbanisation [9,10]. Additionally, increase in rural electrification has contributed to the rise in electricity consumption [11]. However, in the future the same factors would contribute to the growth in electricity consumption as Pakistan would aim to transit itself in the league of developed countries [12]. Efforts have been made to explore and exploit the indigenous energy resources. Despite the struggles, the imports of energy are about 30% of the total consumption [13]. In the imports, the major part (i.e., ~88%) is of oil (i.e., crude oil and petroleum products), in which, a major share is used for power generation [14]. Any oil price change in the global market extremely influences Pakistan's energy generation rendering existing circular debt issue even more seriously [15].

Pakistan's current installed electricity capacity is 25,000 MW and it is not sufficient to meet the existing electricity demand

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The role that battery and water storage play in Saudi Arabia's transition to an integrated 100% renewable energy power system

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ABSTRACT

Saudi Arabia can transition to a 100% renewable energy system by 2040 including the integration of the power, desalination and non-energetic industrial gas sectors. Single-axis tracking PV and battery storage contribute the highest to the final LCOE of the system. By 2050, single-axis tracking PV accounts for 79% of the total electricity generation. Battery storage accounts for 30% of the total electricity demand. Battery storage and desalination plants provide additional flexibility to the energy system. Through sensitivity analysis, it is found that decreasing the capex of desalination plants results in lower full load hours (FLH) and a decrease in battery storage output. This results in lower energy system costs. However, the SWRO capex has to be reduced by 50% to achieve a reduction of 1% in SWRO FLH and a 2.1% in the annualised energy system costs. This is because it is preferable to run the expensive SWRO plants in baseload operation for total energy system cost reasons. Flexibility to the energy system can be provided at a lower cost by solar PV and battery storage than by SWRO plants and water storage. Decreasing battery capex reduces the flexibility of desalination plants further, increases single-axis tracking PV capacities, decreases wind and CCGT capacities, and ultimately results in lower LCOE. These insights enable to establish the least cost pathway for Saudi Arabia to achieve net zero emissions by mid-century.

1. Introduction

Energy storage is seen as a cornerstone of the green energy revolution [1,2]. The intermittent nature of solar and wind resources can be overcome with different types of flexibility (supply side management, demand side management, grids, sector coupling, storage), thereof energy storage is regarded as one of the most important, enabling a faster transition towards a 100% renewable energy system [3–5]. With the increase in global installed capacities of renewable energy power plants, there is a surge in demand for energy storage capacities. The Bloomberg New Energy Finances (BNEF) New Energy Outlook 2016 report forecasts the storage capacity to increase to 25 GW by 2028 from the 1 GW installed today [6].

Luo et al. [2] provides an overview of the current storage technologies and explains that pumped hydro storage (PHS) accounts for 99% of the global storage capacities. However, with improved power to energy ratios, Lithium-ion batteries are currently experiencing by far the fastest growth of all storage options and being used in small and utility-scale applications [2]. Consequently, there has been a sharp decline in the capex of batteries as presented by Liebreich from BNEF [7]. The price of the electric vehicle (EV) lithium ion battery price is estimated to have fallen from 770 €/kWh in 2010 to 243 €/kWh in 2015 [7]. The report forecasts the cost to plunge even more sharply to 162 €/kWh by 2018, a 77% fall in cost between 2010 and 2018. Based on the discussed learning curve rate of 14% - 19%, the capital cost of electric vehicles is expected to arrive at parity with internal combustion engine cars by 2022 [7]. Tesla is reported to project even steeper cost reductions with cost of electric vehicle battery packs dropping to 100 USD/kWh by 2020 [8]. These projections are further supported by Kittner et al. [9], who based on their model, expect electric vehicles to be cost competitive with combustion engine vehicles as early as 2017 and no later than 2020. The core technology of Li-ion batteries does not differ substantially between mobile and stationary applications. Thus, cost reductions in one type of battery storage also translates to cost reductions in other applications. Schmidt et al. [10] analyses future cost projections for electrical energy storage, based on learning curves. The learning rate for lithium ion battery storage in electric vehicles is estimated to be 16%. Meanwhile, lithium ion battery storage in electronics has the steepest learning rate with 30%. Utility and residential scale applications had a lower learning rate of 12% in the past. Breyer

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Analysis of 100% renewable energy for Iran in 2030: integrating solar PV, wind energy and storage

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Abstract

The devastating effects of fossil fuels on the environment, limited natural sources and increasing demand for energy across the world make renewable energy sources more important than in the past. The 2015 United Nations Climate Change Conference resulted in a global agreement on net zero CO_2 emissions shortly after the middle of the twenty-first century, which will lead to a collapse of fossil fuel demand. The focus of the study is to define a cost optimal 100% renewable energy system in Iran by 2030 using an hourly resolution model. The optimal sets of renewable energy technologies, least-cost energy supply, mix of capacities and operation modes were calculated and the role of storage technologies was examined. Two scenarios have been evaluated in this study: a country-wide scenario and an integrated scenario. In the country-wide scenario, renewable energy generation and energy storage technologies cover the country's power sector electricity demand. In the integrated scenario, the renewable energy generated was able to fulfil both the electricity demand of the power sector and the substantial electricity demand for water desalination and synthesis of industrial gas. By adding sector integration, the total levelized cost of electricity decreased from 45.3 to 40.3 €/MWh. The levelized cost of electricity of 40.3 €/MWh in the integrated scenario is quite cost-effective and beneficial in comparison with other low-carbon but high-cost alternatives such as carbon capture and storage and nuclear energy. A 100% renewable energy system for Iran is found to be a real policy option.

Keywords

RESEARCH ARTICLE

Hydro, wind and solar power as a base for a 100% renewable energy supply for South and Central America

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Abstract

Power systems for South and Central America based on 100% renewable energy (RE) in the year 2030 were calculated for the first time using an hourly resolved energy model. The region was subdivided into 15 sub-regions. Four different scenarios were considered: three according to different high voltage direct current (HVDC) transmission grid development levels (region, country, area-wide) and one integrated scenario that considers water desalination and industrial gas demand supplied by synthetic natural gas via power-to-gas (PtG). RE is not only able to cover 1813 TWh of estimated electricity demand of the area in 2030 but also able to generate the electricity needed to fulfil 3.9 billion m^3 of water desalination and 640 TWh_{LHV} of synthetic natural gas demand. Existing hydro dams can be used as virtual batteries for solar and wind electricity storage, diminishing the role of storage technologies. The results for total levelized cost of electricity (LCOE) are decreased from 62 €/MWh for a highly decentralized to 56 €/MWh for a highly centralized grid scenario (currency value of the year 2015). For the integrated scenario, the levelized cost of gas (LCOG) and the levelized cost of water (LCOW) are 95 €/MWh_{LHV} and 0.91 €/m^3, respectively. A reduction of 8% in total cost and 5% in electricity generation was achieved when integrating desalination and power-to-gas into the system.

Introduction

South and Central America are economically emerging regions that have had sustained economic growth and social development during the last decade. The regions' 3% gross domestic product (GDP) growth rate [1] followed by an estimated fast-paced electricity demand growth over the coming decades [2] requires the development of the power sector in order to guarantee efficiency and security of supply.

The South and Central American electrical energy mix is the least carbon-intensive in the world due to the highest share of renewable energy, mainly based on hydropower installed capacities [3, 4]. However, the need to reduce the vulnerability of the electricity system to a

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Article

A Cost Optimized Fully Sustainable Power System for Southeast Asia and the Pacific Rim

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Abstract: In this paper, a cost optimal 100% renewable energy based system is obtained for Southeast Asia and the Pacific Rim region for the year 2030 on an hourly resolution for the whole year. For the optimization, the region was divided into 15 sub-regions and three different scenarios were set up based on the level of high voltage direct current grid connections. The results obtained for a total system levelized cost of electricity showed a decrease from 66.7 €/MWh in a decentralized scenario to 63.5 €/MWh for a centralized grid connected scenario. An integrated scenario was simulated to show the benefit of integrating additional demand of industrial gas and desalinated water which provided the system the required flexibility and increased the efficiency of the usage of storage technologies. This was reflected in the decrease of system cost by 9.5% and the total electricity generation by 5.1%. According to the results, grid integration on a larger scale decreases the total system cost and levelized cost of electricity by reducing the need for storage technologies due to seasonal variations in weather and demand profiles. The intermittency of renewable technologies can be effectively stabilized to satisfy hourly demand at a low cost level. A 100% renewable energy based system could be a reality economically and technically in Southeast Asia and the Pacific Rim with the cost assumptions used in this research and it may be more cost competitive than the nuclear and fossil carbon capture and storage (CCS) alternatives.

Keywords: 100% renewable energy; Southeast Asia; Australia; energy system optimization; storage; grid integration; economics

1. Introduction

Electricity is a significant factor for rapid industrialization, urbanization and improving quality of life [1]. In the 21st century, demand for electricity is rising and will continue to do so due to industrialization in developing and emerging countries. Providing affordable, accessible, reliable, low to zero carbon electricity in developing and emerging countries will be the main aim of electricity generation in the next decades [2]. The region of Southeast Asia and the Pacific Rim (from hereafter Southeast Asia and the Pacific Rim will be called Southeast Asia) consists of developed countries such as Australia, New Zealand and Singapore, as well as fast developing and emerging economies such as Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Papua New Guinea, the Philippines, Thailand, Timor-Leste and Vietnam [3]. The developing region was home to approximately 630 million people in the year 2015 [4] and the need for energy has been higher and growing rapidly due to increasing population and industrialization since the Asian Financial Crisis of 1997–1998 [5–7]. To sustain growth and development, demand for electricity will be 3–4 times the demand of the year 2013 by 2040 [5]. On the other hand, Australia and New Zealand, which are well developed economies, have higher per capita electricity use than the Southeast Asian member states. Australia has one of the highest emissions per capita in the developed world due to its use of coal in electricity generation [8]. To overcome

RESEARCH ARTICLE

Electricity system based on 100% renewable energy for India and SAARC

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Abstract

The developing region of SAARC (South Asian Association for Regional Cooperation) is home to a large number of people living below the poverty line. In future, providing affordable, universally accessible, reliable, low to zero carbon electricity in this region will be the main aim. A cost optimal 100% renewable energy system is simulated for SAARC for the year 2030 on an hourly resolved basis. The region was divided into 16 sub-regions and three different scenarios were set up based on the level of high voltage direct current (HVDC) grid connections. The results obtained for a total system levelised cost of electricity (LCOE) showed a decrease from 71.6 €/MWh in a decentralized to 67.2 €/MWh for a centralized grid connected scenario. An additional scenario was simulated to show the benefits of integrating industrial gas production and seawater reverse osmosis desalination demand, and showed the system cost decreased by 5% and total electricity generation decreased by 1%. The results show that a 100% renewable energy system could be a reality in the SAARC region with the cost assumptions used in this research and it may be more cost competitive than nuclear and fossil carbon capture and storage (CCS) alternatives. One of the limitations of this study is the cost of land for installation of renewables which is not included in the LCOE calculations, but regarded as a minor contribution.

1. Introduction

Energy is critical, directly or indirectly, to the entire process of evolution, growth and survival of all living beings. In addition, it plays a vital role in the socio-economic development and human welfare of a country, and any uncertainty in its supply can threaten the functioning of an economy, particularly in developing countries [1]. The region of interest for this research is the developing region of South Asia, which is made up of the following countries: Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka. Collectively, they are also called SAARC (South Asian Association for Regional Cooperation). Providing affordable, universally accessible, reliable, low to zero carbon electricity in the developing countries will be the main aim of electricity generation in the next decades [2]. A report published by WWF lists ten recommendations for a 100% renewable energy (RE) future. The top two recommendations include, firstly, developing new and existing renewable energy sources to provide

sustainability

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Article

Can Australia Power the Energy-Hungry Asia with Renewable Energy?

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Abstract: The Paris Agreement points out that countries need to shift away from the existing fossil-fuel-based energy system to limit the average temperature rise to 1.5 or 2 °C. A cost-optimal 100% renewable energy based system is simulated for East Asia for the year 2030, covering demand by power, desalination, and industrial gas sectors on an hourly basis for an entire year. East Asia was divided into 20 sub-regions and four different scenarios were set up based on the level of high voltage grid connection, and additional demand sectors: power, desalination, industrial gas, and a renewable-energy-based synthetic natural gas (RE-SNG) trading between regions. The integrated RE-SNG scenario gives the lowest cost of electricity (€52/MWh) and the lowest total annual cost of the system. Results contradict the notion that long-distance power lines could be beneficial to utilize the abundant solar and wind resources in Australia for East Asia. However, Australia could become a liquefaction hub for exporting RE-SNG to Asia and a 100% renewable energy system could be a reality in East Asia with the cost assumptions used. This may also be more cost-competitive than nuclear and fossil fuel carbon capture and storage alternatives.

Keywords: East Asia; Australia; 100% renewable energy; power-to-gas; synthetic natural gas; grid integration; system optimization; economics

1. Introduction

In December 2015, the annual Conference of Parties (COP) 21 held in Paris, also known as the Paris Agreement [1] was an action-driven event with several concreate achievements [2]. The conference presented several political and business leaders with the opportunity to take the critical decisions needed to keep the average global temperature rise to no more than 1.5 or 2 °C, which finally requires net zero greenhouse gas emissions shortly after the middle of this century [1]. According to Schellnhuber et al. [3], the 2 °C limit is economically achievable due to rapidly falling costs of renewable energy, particularly solar PV, but is constrained by politics. It is observed that change is happening in energy supply for a lot of countries, but this needs to happen faster. The region of interest for this research is East Asia, which is comprised of Northeast Asia and Southeast Asia, the latter including Australia and New Zealand.

Energy is a key driver for social and economic development, particularly in developing countries where many people have no access to basic forms of energy. Many developing countries have programs to electrify the non-electrified population and at the same time maintain a high level of economic development. Thus, the demand for electricity is growing very fast, particularly in East Asia. According to Taggart [4], leading up to 2050, East Asia—comprised of China, Japan, the ASEAN states, and Australia—will become the world's largest economy. To keep up with economic development and improve living conditions, there will be a rapid increase in energy needs, which will put our climate at risk, as the energy sector is one of the main sources of greenhouse gas

energies

MDPI

Article

A Techno-Economic Study of an Entirely Renewable Energy-Based Power Supply for North America for 2030 Conditions

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Abstract: In this study power generation and demand are matched through a least-cost mix of renewable energy (RE) resources and storage technologies for North America by 2030. The study is performed using an hourly resolved model based on a linear optimization algorithm. The geographical, technical and economic potentials of different forms of RE resources enable the option of building a super grid between different North American regions. North America (including the U.S., Canada and Mexico in this paper), is divided into 20 sub-regions based on their population, demand, area and electricity grid structure. Four scenarios have been evaluated: region-wide, country-wide, area-wide and an integrated scenario. The levelised cost of electricity is found to be quite attractive in such a system, with the range from 63 €/MWh_{el} in a decentralized case and 42 €/MWh_{el} in a more centralized and integrated scenario. Electrical grid interconnections significantly reduce the storage requirement and overall cost of the energy system. Among all RE resources, wind and solar PV are found to be the least-cost options and hence the main contributors to fossil fuel substitution. The results clearly show that a 100% RE-based system is feasible and a real policy option at a modest cost. However, such a tremendous transition will not be possible in a short time if policy-makers, energy investors and other relevant organizations do not support the proposed system.

Keywords: energy scenario; energy system modelling; solar PV; wind power; energy storage; North America; Canada; United States; Mexico

1. Introduction

Over the past few decades, global population has increased and living standards have advanced dramatically in many parts of the world. Consequently, energy demand is increasing, particularly in the Organization for Economic Cooperation and Development (OECD) countries due to their high economic development and advanced lifestyle. In fact, although the U.S. has less than 5% of the world's population [1], it consumes as much as 25% of the global primary energy used [2]. Increasing world population will lead to several formidable challenges, such as climate change, a greater gap between energy demand and supply, and depletion of fossil fuel resources. Phasing out nuclear and fossil fuels is unlikely to be generally acceptable, but eliminating greenhouse gas emissions, known also as the "net zero emissions" target by mid-21st century agreed at Conference of the Parties (COP21) in Paris, clearly guides the pathway towards sustainability [3].

The technical, geographical and economic potentials of various forms of renewable energy (RE) resources in North America enable a lucrative "super grid" connection between the continent's regional energy systems to obtain synergy effects and make a 100% RE supply possible [4–7]. North America's wealth of RE resources are comprised of solar energy, wind energy, hydropower, geothermal, biomass and waste-to-energy resources. As the cost of RE technologies begins to compete with that of

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100% renewable electricity in Australia

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A B S T R A C T

An hourly energy balance analysis is presented of the Australian National Electricity Market in a 100% renewable energy scenario, in which wind and photovoltaics (PV) provides about 90% of the annual electricity demand and existing hydroelectricity and biomass provides the balance. Heroic assumptions about future technology development are avoided by only including technology that is being deployed in large quantities (>10 Gigawatts per year), namely PV and wind.

Additional energy storage and stronger interconnection between regions was found to be necessary for stability. Pumped hydro energy storage (PHES) constitutes 97% of worldwide electricity storage, and is adopted in this work. Many sites for closed loop PHES storage have been found in Australia. Distribution of PV and wind over 10–100 million hectares, utilising high voltage transmission, accesses different weather systems and reduces storage requirements (and overall cost).

The additional cost of balancing renewable energy supply with demand on an hourly rather than annual basis is found to be modest: AU$25–30/MWh (US$19–23/MWh). Using 2016 prices prevailing in Australia, the levelised cost of renewable electricity (LCOE) with hourly balancing is estimated to be AU$93/MWh (US$70/MWh). LCOE is almost certain to decrease due to rapidly falling cost of wind and PV.

1. Introduction

In this paper, Australian dollars are used and an exchange rate of AU$1.00 = US$0.75 is assumed.

It is interesting to consider the practicalities of supplying all of Australia's electricity from renewable energy. In this study a scenario is developed in which the National Electricity Market (NEM) is exclusively supplied by renewable energy. The focus is on hourly energy balance (meeting demand for every hour of the year).

Deployment of wind and solar photovoltaic (PV) electricity is overwhelmingly dominant in terms of new low emissions generation technology because they cost less than alternatives. PV and wind constitute half of the world's new generation capacity installed in 2014–16 (Fig. 1). In recent years, these sources provided nearly all new generation capacity installed in Australia.

In Australia, wind and PV are unconstrained by land or resource availability or water requirements or material supply or security issues. Hydro power is unable to keep pace due to the constraint that there are a limited number of rivers to dam, and bioenergy is severely limited by sustainable biomass availability [4,5]. Heroic growth rates are required for other renewable or low emission technologies (nuclear, carbon capture & storage, concentrating solar thermal, ocean, geothermal) to span the 10–1000-fold difference in annual deployment (GW per year) to approach the scale of wind and PV – which are moving targets since both industries are themselves growing rapidly and both access large economies of scale.

Currently, two thirds of Australian electricity comes from coal fired power stations. However, by 2030, three quarters of these power stations will be more than 40 years old, and replacement of these generators by coal, gas or renewable energy will be a looming necessity. For instance, Wallerawang C 960 MW (NSW), Anglesea 150 MW (Victoria) and Northern 530 MW (South Australia) and Hazelwood 1640 MW (Victoria) were closed during 2013–17 [6,7]. It seems unlikely that more coal fired generators will be constructed in Australia due to public opposition and risk aversion of financiers. In contrast, there is strong financial support for wind and PV in Australia, as evidenced by the fact that about 9 GW of wind and PV will be constructed over the next 3 years [8] in an economy whose GDP is about one thirteenth that of the United States of America.

Australia has excellent wind and solar resources. If current deployment rates of PV and wind (approximately 1–2 GW per year of each) continue then about half of the electricity generated in

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90–100% renewable electricity for the South West Interconnected System of Western Australia

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ABSTRACT

Rapidly increasing penetration of renewables, primarily wind and photovoltaics (PV), is causing a move away from fossil fuel in the Australian electric power industry. This study focuses on the South West Interconnected System in Western Australia. Several high (90% and 100%) renewables penetration scenarios have been modelled, comprising wind and PV supplemented with a small amount of biogas, and compared with a "like-for-like" fossil-fuel replacement scenario. Short-term off-river (closed cycle) pumped hydro energy storage (PHES) is utilised in some simulations as a large-scale conventional storage technology. The scenarios are examined by using a chronological dispatch model. An important feature of the modelling is that only technologies that have been already deployed on a large scale (>150 gigawatts) are utilised. This includes wind, PV and PHES. The modelling results demonstrate that 90–100% penetration by wind and PV electricity is compatible with a balanced grid. With the integration of off-river PHES, 90% renewables penetration is able to provide low-carbon electricity at competitive prices. Pumped hydro also facilitates a 100% renewables scenario which produces zero greenhouse gas emissions with attractive electricity prices. A sensitivity analysis shows the most important factors in the system cost are discount rate and wind turbine cost.

1. Introduction

1.1. Decarbonisation of Australian energy sector

Australia announced its 2030 Emission Reduction Target at the historic Paris Agreement on climate change, namely to reduce greenhouse gas (GHG) emissions by 26–28% below 2005 levels by 2030 [1]. This translates to emission reductions of 50–52% per capita, although these figures are considerably smaller if a different baseline year is selected. Australia's annual GHG emissions have averaged 570 Mt CO2-e over the last decade with around two thirds produced by energy-related sectors including stationary energy, transport and fugitive emissions [2]. Electricity generation, currently dominated by fossil-fuel power stations, is the largest source of emissions accounting for around one third of the total.

Low carbon electricity has the greatest potential for rapid decarbonisation of the energy sector [3]. This is the approach adopted by the Australian Capital Territory (ACT) Government to achieve its early GHG target of 100% renewable electricity by 2020 [4]. Wind and photovoltaics (PV) systems constitute virtually all new generation systems in Australia now and for the foreseeable future. Over the last decade, wind power has grown at an annual average rate of 22% with a total installed capacity of about 4 GW at the end of 2015. Solar PV has seen even stronger growth, dominated by residential solar installations, rising from around 4 MW to 5 GW. Wind and PV contributed about 18 TWh in Australia in 2015, compared with hydroelectricity (14 TWh) and biomass electricity (3 TWh) [5].

New capacity installations in the worldwide renewable electricity industry is heavily dominated by wind and PV, which are unconstrained by resource availability or water requirements or material supply or security issues. Together, wind and PV constituted about half of new generation capacity installed in 2015 (Fig. 1). Hydro power is unable to expand considerably due to lack of rivers to dam, and bioenergy is severely limited by biomass availability [6]. Heroic growth rates are required for other renewable or low emission technologies (nuclear, carbon capture & storage, concentrating solar thermal, ocean, geothermal) to span the 20 to 1000-fold difference in scale to catch up with wind and PV

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Vision and initial feasibility analysis of a recarbonised Finnish energy system for 2050

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ABSTRACT

An energy system based entirely on renewable energy (RE) is possible for Finland in 2050 based on the assumptions in this study. High shares of solar PV (photovoltaics) were deemed to be feasible at extreme northern latitudes when supported by flexibility harnessed from other aspects of the energy system, suggesting that high variations in solar irradiation throughout the year may not be a barrier to the implementation of solar PV closer to the poles. A 100% RE system corresponds to a highly competitive cost solution for Finland, as total system costs decrease through interaction between the power, heating/cooling and mobility sectors. We incorporate these sectors on an hourly resolution using historical data and the EnergyPLAN modelling tool. In addition, we offer full transparency of all assumptions regarding the Finnish energy system. In 2050, a 100% renewable energy scenario has the lowest overall annual cost, at 24.1 b€/a. This is followed by several scenarios that feature increasing levels of nuclear power, which range in annual costs to 26.4 b€/a. Scenarios were also modelled with varying levels of forest-based biomass. Results suggest that annual costs do not increase dramatically with reduced levels of forest-based biomass fuel use. At the same time, it must be kept in mind that assigning costs to the future is inherently uncertain. How future societies assign risk to technologies or place value on emissions can make the scenarios under investigation more or less attractive. The 100% RE scenarios under investigation were seen as less exposed to such uncertainty.

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Abbreviations: RE, renewable energy; PV, photovoltaic; GHG, greenhouse gas; LPG, liquid petroleum gas; CHP, combined heat and power; DH, district heating; BAU, business as usual; $_e$, electric units; $_{th}$, thermal units; $_{gas}$, gas units; $_p$, nominal or peak capacity; TPED, total primary energy demand; PtG, Power-to-gas; PtL, Power-to-liquid; PtX, Power-to-chemical; V2G, Vehicle-to-grid; BEV, Battery electric vehicle; Capex, Capital expenditures; Opex, Operating and maintenance expenditures; LCOE, Levelized cost of electricity; WACC, Weighted average cost of capital; Crf, Capital recovery factor; GDP, Gross Domestic Product

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Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union

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ABSTRACT

This study presents one scenario for a 100% renewable energy system in Europe by the year 2050. The transition from a business-as-usual situation in 2050, to a 100% renewable energy Europe is analysed in a series of steps. Each step reflects one major technological change. For each step, the impact is presented in terms of energy (primary energy supply), environment (carbon dioxide emissions), and economy (total annual socio-economic cost). The steps are ordered in terms of their scientific and political certainty as follows: decommissioning nuclear power, implementing a large amount of heat savings, converting the private car fleet to electricity, providing heat in rural areas with heat pumps, providing heat in urban areas with district heating, converting fuel in heavy-duty vehicles to a renewable electrofuel, and replacing natural gas with methane. The results indicate that by using the *Smart Energy System* approach, a 100% renewable energy system in Europe is technically possible without consuming an unsustainable amount of bioenergy. This is due to the additional flexibility that is created by connecting the electricity, heating, cooling, and transport sectors together, which enables an intermittent renewable penetration of over 80% in the electricity sector. The cost of the *Smart Energy Europe* scenario is approximately 10–15% higher than a business-as-usual scenario, but since the final scenario is based on local investments instead of imported fuels, it will create approximately 10 million additional direct jobs within the EU.

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North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options

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ABSTRACT

In order to define a cost optimal 100% renewable energy system, an hourly resolved model has been created based on linear optimization of energy system parameters under given constrains. The model is comprised of five scenarios for 100% renewable energy power systems in North-East Asia with different high voltage direct current transmission grid development levels, including industrial gas demand and additional energy security. Renewables can supply enough energy to cover the estimated electricity and gas demands of the area in the year 2030 and deliver more than 2000 TW h_{th} of heat on a cost competitive level of 84 €/MW h_{el} for electricity. Further, this can be accomplished for a synthetic natural gas price at the 2013 Japanese liquefied natural gas import price level and at no additional generation costs for the available heat. The total area system cost could reach 69.4 €/MW h_{el}, if only the electricity sector is taken into account. In this system about 20% of the energy is exchanged between the 13 regions, reflecting a rather decentralized character which is supplied 27% by stored energy. The major storage technologies are batteries for daily storage and power-to-gas for seasonal storage. Prosumers are likely to play a significant role due to favourable economics. A highly resilient energy system with very high energy security standards would increase the electricity cost by 23% to 85.6 €/MW h_{el}. The results clearly show that a 100% renewable energy based system is feasible and lower in cost than nuclear energy and fossil carbon capture and storage alternatives.

1. Introduction

Fast economic growth in the North-East Asian region provoked an extensive rise in electricity demand, based mainly on fossil fuel utilization, in the last decades [1]. Increasing ecological and social problems are caused by the fossil fuel based energy system, including increased anthropogenic pressure on nature in general [2] and an ongoing destruction of ecosystems all around the world [3]. This anthropogenic pressure leads in particular to climate change [4], which will have a dramatic negative impact on the economy on a global scale, as concluded by Stern [5]. Harmful and costly consequences of coal-based air pollution [6] have to be further taken into account for the full societal cost of energy supply. These issues drive the idea for a renewable energy (RE) based system development up to 100% RE [7] and the discussion of its competitiveness on a global scale [8] and in a rather distributed manner [9]. It is feasible that RE based systems can decrease the anthropological footprint [10] in particular since the most important RE technologies show a continued strong growth and the large majority of countries in the world have introduced respective policies [11].

Scenarios of energy systems based on very high shares of RE had been already discussed for several countries and regions. Connolly and Mathiesen [12] showed for the case of Ireland in an hourly modeling that 100% RE is technically feasible and economic affordable. Henning and Palzer [13] discussed that a 100% RE system for the sectors electricity and heat is technically doable and the cost are comparable to the current energy system, also based on hourly resolution. Thellufsen and Lund [14] pointed out that energy efficiency measures in the electricity and heat sector can even generate positive synergies for 100% RE for the example of Denmark. Critz et al. [15] emphasized that demand response measures help to integrate a high penetration of renewables into the existing system and that it can reduce the overall cost for the case of Hawaii. Huber et al. [16] found on the case of the ASEAN region that a well balanced mix of renewable resources and a geographic integration of a larger region is required for balancing high shares of RE.

Komoto et al. [17] proposed very large scale solar photovoltaic power plants for North-East Asia pointing out that excellent renewable resources of a large unpopulated region, such as the Gobi desert, can be utilized for a very large region by applying a

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Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes

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This study addresses the greatest concern facing the large-scale integration of wind, water, and solar (WWS) into a power grid: the high cost of avoiding load loss caused by WWS variability and uncertainty. It uses a new grid integration model and finds low-cost, no-load-loss, nonunique solutions to this problem on electrification of all US energy sectors (electricity, transportation, heating/cooling, and industry) while accounting for wind and solar time series data from a 3D global weather model that simulates extreme events and competition among wind turbines for available kinetic energy. Solutions are obtained by prioritizing storage for heat (in soil and water); cold (in ice and water); and electricity (in phase-change materials, pumped hydro, hydropower, and hydrogen), and using demand response. No natural gas, biofuels, nuclear power, or stationary batteries are needed. The resulting 2050–2055 US electricity social cost for a full system is much less than for fossil fuels. These results hold for many conditions, suggesting that low-cost, reliable 100% WWS systems should work many places worldwide.

energy security | climate change | grid stability | renewable energy | energy cost

Worldwide, the development of wind, water, and solar (WWS) energy is expanding rapidly because it is sustainable, clean, safe, widely available, and, in many cases, already economical. However, utilities and grid operators often argue that today's power systems cannot accommodate significant variable wind and solar supplies without failure (1). Several studies have addressed some of the grid reliability issues with high WWS penetrations (2–21), but no study has analyzed a system that provides the maximum possible long-term environmental and social benefits, namely supplying all energy end uses with only WWS power (no natural gas, biofuels, or nuclear power), with no load loss at reasonable cost. This paper fills this gap. It describes the ability of WWS installations, determined consistently over each of the 48 contiguous United States (CONUS) and with wind and solar power output predicted in time and space with a 3D climate/weather model, accounting for extreme variability, to provide time-dependent load reliably and at low cost when combined with storage and demand response (DR) for the period 2050–2055, when a 100% WWS world may exist.

Materials and Methods

The key to this study is the development of a grid integration model (LOADMATCH). Inputs include time-dependent loads (every 30 s for 6 y); time-dependent intermittent wind and solar resources (every 30 s for 6 y) predicted with a 3D global climate/weather model; time-dependent hydropower, geothermal, tidal, and wave resources; capacities and maximum charge/discharge rates of several types of storage technologies, including hydrogen (H_2); specifications of losses from storage, transmission, distribution, and maintenance; and specifications of a DR system.

Loads and Storage. CONUS loads for 2050–2055 for use in LOADMATCH are derived as follows. Annual CONUS loads are first estimated for 2050 assuming each end-use energy sector (residential, transportation, commercial, industrial) is converted to electricity and some electrolytic hydrogen after accounting for modest improvements in end-use energy efficiency (22). Annual loads in each sector are next separated into cooling and heating loads that can be met with thermal energy storage (TES), loads that can be met with hydrogen production and storage, flexible loads that can be met with DR, and inflexible loads (Table 1).

Most (50–95%) air conditioning and refrigeration and most (85–95%) air heating and water heating are coupled with TES (Table 1). Cooling coupled with storage is tied to chilled water (sensible-heat) TES (STES) and ice production and melting [phase-change material (PCM)-ice] (*SI Appendix*, Table S1). All building air- and water-heating coupled with storage uses underground TES (UTES) in soil. UTES storage is patterned after the seasonal and short-term district heating UTES system at the Drake Landing Community, Canada (23). The fluid (e.g., glycol solution) that heats water that heats the soil and rocks is itself heated by sunlight or excess electricity.

Overall, 85% of the transportation load and 70% of the loads for industrial high temperature, chemical, and electrical processes are assumed to be flexible or produced from H_2 (Table 1).

Six types of storage are treated (*SI Appendix*, Table S1): three for air and water heating/cooling (STES, UTES, and PCM-ice); two for electric power generation [pumped hydropower storage (PHS) and phase-change materials coupled with concentrated solar power plants (PCM-CSP)]; and one for transport or high-temperature processes (hydrogen). Hydropower (with reservoirs) is treated as an electricity source on demand, but because reservoirs can be recharged only naturally they are not treated as artificially rechargeable storage. Lithium-ion batteries are used to power battery-electric vehicles but to avoid battery degradation, not to feed power from vehicles to the grid. Batteries for stationary power storage work well in this system too. However, because they currently cost more than the other storage technologies used (24), they are prioritized lower and are found not

Significance

The large-scale conversion to 100% wind, water, and solar (WWS) power for all purposes (electricity, transportation, heating/cooling, and industry) is currently inhibited by a fear of grid instability and high cost due to the variability and uncertainty of wind and solar. This paper couples numerical simulation of time- and space-dependent weather with simulation of time-dependent power demand, storage, and demand response to provide low-cost solutions to the grid reliability problem with 100% penetration of WWS across all energy sectors in the continental United States between 2050 and 2055. Solutions are obtained without higher-cost stationary battery storage by prioritizing storage of heat in soil and water; cold in water and ice; and electricity in phase-change materials, pumped hydro, hydropower, and hydrogen.

Author contributions: M.Z.J. designed research; M.Z.J. and M.A.D. performed research; M.Z.J., M.A.D., M.A.C., and B.A.F. contributed analytic tools; M.Z.J., M.A.D., and M.A.C. analyzed data; and M.Z.J., M.A.D., M.A.C., and B.A.F. wrote the paper.

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Smart Energy Systems for coherent 100% renewable energy and transport solutions

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HIGHLIGHTS

- Integrating smart electricity, smart thermal and smart gas grids to enable 100% RE.
- Cost and fuel synergies across electricity, heating, and transport can be exploited.
- Focusing only on a smart electricity grid reduces the potential for fluctuating RE.
- Smart Energy System design can ensure biomass use is limited to a sustainable level.
- Smart Energy Systems can pave the way for bioenergy-free 100% RES incl. transport.

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ABSTRACT

The hypothesis of this paper is that in order to identify least cost solutions of the integration of fluctuating renewable energy sources into current or future 100% renewable energy supplies one has to take a Smart Energy Systems approach. This paper outline why and how to do so. Traditionally, significant focus is put on the electricity sector alone to solve the renewable energy integration puzzle. Smart grid research traditionally focuses on ICT, smart meters, electricity storage technologies, and local (electric) smart grids. In contrast, the Smart Energy System focuses on merging the electricity, heating and transport sectors, in combination with various intra-hour, hourly, daily, seasonal and biannual storage options, to create the flexibility necessary to integrate large penetrations of fluctuating renewable energy. However, in this paper we present the development and design of coherent Smart Energy Systems as an integrated part of achieving future 100% renewable energy and transport solutions. The transition from fossil fuels towards the integration of more and more renewable energy requires rethinking and redesigning the energy system both on the generation and consumption side. To enable this, the Smart Energy System must have a number of appropriate infrastructures for the different sectors of the energy system, which are smart electricity grids, smart thermal grids (district heating and cooling), smart gas grids and other fuel infrastructures. It enables fluctuating renewable energy (such as wind, solar, wave power and low value heat sources) to utilise new sources of flexibility such as solid, gaseous, and liquid fuel storage, thermal storage and heat pumps and battery electric vehicles. Smart Energy Systems also enable a more sustainable and feasible use of bioenergy than the current types allow. It can potentially pave the way to a bioenergy-free 100% renewable energy and transport system.

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Comparing least cost scenarios for 100% renewable electricity with low emission fossil fuel scenarios in the Australian National Electricity Market

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A B S T R A C T

Policy makers face difficult choices in planning to decarbonise their electricity industries in the face of significant technology and economic uncertainties. To this end we compare the projected costs in 2030 of one medium-carbon and two low-carbon fossil fuel scenarios for the Australian National Electricity Market (NEM) against the costs of a previously published scenario for 100% renewable electricity in 2030. The three new fossil fuel scenarios, based on the least cost mix of baseload and peak load power stations in 2010, are: (i) a medium-carbon scenario utilising only gas-fired combined cycle gas turbines (CCGTs) and open cycle gas turbines (OCGTs); (ii) coal with carbon capture and storage (CCS) plus peak load OCGT; and (iii) gas-fired CCGT with CCS plus peak load OCGT. We perform sensitivity analyses of the results to future carbon prices, gas prices, and CO_2 transportation and storage costs which appear likely to be high in most of Australia. We find that only under a few, and seemingly unlikely, combinations of costs can any of the fossil fuel scenarios compete economically with 100% renewable electricity in a carbon constrained world. Our findings suggest that policies pursuing very high penetrations of renewable electricity based on commercially available technology offer a cost effective and low risk way to dramatically cut emissions in the electricity sector.

1. Introduction

There is a growing recognition of the urgency for large, rapid and sustained emissions reductions to avoid dangerous global warming. Achieving deep cuts to greenhouse gas emissions in some sectors (e.g., transportation, agriculture) is likely to be more difficult than the electricity sector. The Australian Government has a policy to reduce greenhouse gas emissions to 80% below year 2000 levels by 2050. Electricity generation in the Australian National Electricity Market (NEM) is responsible for around one third of national emissions [1] and is therefore an obvious candidate for early efforts to reduce emissions. Given the availability of low carbon options for electricity generation, it could be argued that the electricity sector should be almost completely decarbonised to contribute towards the 2050 target. One approach to decarbonising the electricity sector being considered world-wide is a transition to 100% renewable energy sources.

In this paper, we compare the cost estimates of previously published scenarios for 100% renewable electricity ("RE100") hour-by-hour in the NEM against a number of alternative options available to policy makers: greater use of efficient gas-fired generation, and the use of carbon capture and storage (CCS). Nuclear power is not examined as it is prohibited in Australia under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999. The key question being addressed is how these alternative scenarios compare with the RE100 scenario and whether they are likely to be significantly lower cost. Indeed, is it worth either deploying gas-fired generation with lower, but still substantial emissions, or waiting for immature CCS technologies to emerge at sufficient scale? The intent of this paper is to help inform policy as governments develop strategies in the face of significant uncertainty about technology development and costs.

The national circumstances of Australia are somewhat unique for a developed country. Australia is a wealthy nation with a well educated workforce and a technological services sector, but with a large share of commodity exports from primary industries. The electricity sector has an ageing fleet of fossil-fuelled thermal generators and is highly emissions intensive by world standards due to

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A technical and economic analysis of one potential pathway to a 100% renewable energy system

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ABSTRACT

This paper outlines how an existing energy system can be transformed into a 100% renewable energy system. The transition is divided into a number of key stages which reflect key radical technological changes on the supply side of the energy system. Ireland is used as a case study, but in reality this reflects many typical energy systems today which use power plants for electricity, individual boilers for heat, and oil for transport. The seven stages analysed are 1) reference, 2) introduction of district heating, 3) installation of small and large-scale heat pumps, 4) reducing grid regulation requirements, 5) adding flexible electricity demands and electric vehicles, 6) producing synthetic methanol/DME for transport, and finally 7) using synthetic gas to replace the remaining fossil fuels. For each stage, the technical and economic performance of the energy system is calculated. The results indicate that a 100% renewable energy system can provide the same end-user energy demands as today's energy system and at the same price. Electricity will be the backbone of the energy system, but the flexibility in today's electricity sector will be transferred from the supply side of the demand side in the future. Similarly, due to changes in the type of spending required in a 100% renewable energy system, this scenario will result in the creation of 100,000 additional jobs in Ireland compared to an energy system like today's. These results are significant since they indicate that the transition to a 100% renewable energy system can begin today, without increasing the cost of energy in the short- or long-term, if the costs currently forecasted for 2050 become a reality.

Keywords:

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1. Introduction

The energy sector is in a state of change and uncertainty. A change is necessary due to the environmental damage and risks associated with the existing energy system such as climate change, pollution, security of supply concerns, and unpredictable future energy prices. Numerous studies, debates, and public figures have highlighted the need for a radical change in the very near future, including the International Energy Agency who have recently stated that a radical change is necessary by 2017 [1].

Unfortunately, the pace of change is relatively slow today, even with all of these concerns and the large body of research to prove that a change is necessary. This could be attributed to numerous factors such as the strength of existing institutions in the energy sector and the lack of suitable policy and markets. In the authors' opinion, one of the key issues obstructing change in the energy sector is uncertainty.

A lot of this uncertainty is created by the variety of alternatives being proposed and debated for the energy sector. Typically, every country will have a few very powerful institutions in each of the electricity, gas, oil, and renewable energy sectors. Each of these institutions would like to remain powerful in the future and so, when debating the design of the future energy system,

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Features of a fully renewable US electricity system: Optimized mixes of wind and solar PV and transmission grid extensions

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ABSTRACT

A future energy system is likely to rely heavily on wind and solar PV. To quantify general features of such a weather dependent electricity supply in the contiguous US, wind and solar PV generation data are calculated, based on 32 years of weather data with temporal resolution of 1 h and spatial resolution of 40×40 km^2, assuming site-suitability-based and stochastic wind and solar capacity distributions. The regional wind-and-solar mixes matching load and generation closest on seasonal timescales cluster around 80% solar share, owing to the US summer load peak. This mix more than halves long-term storage requirements, compared to wind only. The mixes matching generation and load best on daily timescales lie at about 80% wind share, due to the nightly gap in solar production. Going from solar only to this mix reduces backup energy needs by about 50%. Furthermore, we calculate shifts in FERC (Federal Energy Regulatory Commission)-level LCOE (Levelized Costs Of Electricity) for wind and solar PV due to differing weather conditions. Regional LCOE vary by up to 29%, and LCOE-optimal mixes largely follow resource quality. A transmission network enhancement among FERC regions is constructed to transfer high penetrations of solar and wind across FERC boundaries, employing a novel least-cost optimization.

1. Introduction

CO_2 and air pollution emission reduction goals as well as energy security, price stability, and affordability considerations make renewable electricity generation attractive. A highly renewable electricity supply will be based to a large extent on wind and solar photovoltaic (PV) power, since these two resources are both abundant and either relatively inexpensive or rapidly becoming cost competitive [1]. Such a system demands a fundamentally different design approach: While electricity generation was traditionally constructed to be dispatchable in order to follow the demand, wind and solar PV power output is largely determined by weather conditions that are out of human control. We therefore collectively term them VRES (variable renewable energy sources). Spatial aggregation has a favorable impact on generation characteristics, as was found both for wind and solar PV power in numerous studies [2–9]. Especially for wind, smoothing effects are much more pronounced on large scales, as can be seen from the comparison of the US East coast (about 3000×500 km^2), discussed in Ref. [8], to Denmark (about 200×300 km^2), cf. Ref. [9]. In spite of the leveling effects of aggregation, there is still a considerable mismatch between load and generation left, which is partly due also to load variability.

This paper aims to identify general design features for the US power system with a high share of wind and solar PV. While several studies have demonstrated the feasibility of high penetrations of VRES generators in the regional or nationwide US electric system [11–14], these have only evaluated one individual US region and/or have only considered a small set of hours for their analysis. This paper is based on data for the entire contiguous US of unprecedented temporal length and spatial resolution. Relying on 32 years of weather data with hourly time resolution and a spatial resolution of 40×40 km^2, potential future wind and solar PV generation time

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Grid vs. storage in a 100% renewable Europe

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ABSTRACT

Intermittent renewable power production from wind and sun requires significant backup generation to cover the power demand at all times. This holds even if wind and sun produce on average 100% of the required energy. Backup generation can be reduced through storage – averaging in time – and/or grid extensions – averaging in space. This report examines the interplay of these technologies with respect to the reduction of required backup energy. We systematically explore a wide parameter space of combinations of both technologies. Our simple, yet informative approach quantifies the backup energy demand for each scenario. We also estimate the resulting total system costs which allow us to discuss cost-optimal system designs.

1. Introduction

Renewable power generation is growing quickly in Europe. In 2006, the EU defined its 20-20-20 goals calling for 20% renewables in 2020 [1]. Today, already 40% of renewables seem a realistic target for the end of this decade, at least in Germany with its strong photovoltaics (PV) sector [2]. Scenarios with close to 100% renewables are now typically dated for 2050, e.g. [3,4], but they may possibly arrive much earlier.

Yet there is still considerable uncertainty about what a 100% renewable Europe would look like. The largest renewable contributions will probably come from wind turbines and PV, since water, biomass and waste resources are limited. Due to their intermittent nature, significant backup generation is needed for power from wind and sun, even if they cover on average 100% of the demand. This is depicted with an exemplary time line in Fig. 1.

Regarding the required backup *power*, one can see from Fig. 1 that almost the whole demand has to be covered from backup sources alone at certain times. Thus the installed backup capacity should roughly match the peak demand. This is in line with [5] where the capacity credit of wind is rated at only 16%, assuming a well-connected Europe.

The interesting question about the backup system is thus rather how much *energy* the backup power plants have to provide – and how this depends on grid extensions and novel storage capacities. Grids and storage help to reduce backup energy demand by averaging intermittent power generation in space and time. The interplay of these technologies and their effect on the remaining backup energy demand is the central focus of this paper.

Backup energy demand is critical in two respects. First, backup energy would have to come from renewable sources in a fully renewable scenario. The most important source of renewable backup energy is biomass, since only a minimal fraction of Europe's water energy is dispatchable. The yearly energy potential of biomass, however, is limited to roughly 10% of the average power consumption [6]. It could thus be asked under which constellation of generation, grids and storage a fully renewable power system in Europe would be possible at all. For other constellations the backup energy is directly related to remaining CO_2 emissions of the system, since additional backup energy would have to come from fossil sources. Such not fully renewable systems might be acceptable even in the long run, if the financial benefits are significant. The backup energy is thus also an important measure for determining the optimal trade-off between CO_2 emission reduction targets and economic feasibility.

In this paper we use scenarios for Europe where wind and sun, the variable renewable energies (VRE), produce on average 100% or more of the required electric energy. We employ a simple model to quantify the backup energy demand for a wide range of choices of grid and storage. While there are many ways of modelling the different power system components in much greater detail, we think it is important to reduce the problem to the most basic characteristics to maintain an overview and obtain robust order of magnitude results. We also determine optimal system designs. First, optimality means minimising the use of backup energy, a physics perspective. Second, we estimate the financial consequences of each scenario to determine also economically optimal designs.

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Least cost 100% renewable electricity scenarios in the Australian National Electricity Market

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ABSTRACT

Least cost options are presented for supplying the Australian National Electricity Market (NEM) with 100% renewable electricity using wind, photovoltaics, concentrating solar thermal (CST) with storage, hydroelectricity and biofuelled gas turbines. We use a genetic algorithm and an existing simulation tool to identify the lowest cost (investment and operating) scenarios of renewable technologies and locations for NEM regional hourly demand and observed weather in 2010 using projected technology costs for 2030. These scenarios maintain the NEM reliability standard, limit hydroelectricity generation to available rainfall, and limit bioenergy consumption. The lowest cost scenarios are dominated by wind power, with smaller contributions from photovoltaics and dispatchable generation: CST, hydro and gas turbines. The annual cost of a simplified transmission network to balance supply and demand across NEM regions is a small proportion of the annual cost of the generating system. Annual costs are compared with a scenario where fossil fuelled power stations in the NEM today are replaced with modern fossil substitutes at projected 2030 costs, and a carbon price is paid on all emissions. At moderate carbon prices, which appear required to address climate change, 100% renewable electricity would be cheaper on an annual basis than the replacement scenario.

1. Introduction

This paper presents the findings of a study seeking to investigate least cost options for supplying the Australian National Electricity Market (NEM) with 100% renewable electricity in 2030. Different scenarios of technology mix and locations were assessed through simulations of electricity industry operation. A genetic algorithm was used to identify the lowest investment and operating cost scenarios.

The electricity sector is a prime candidate for rapid decarbonisation due to its significant greenhouse gas emissions yet wide range of zero emission supply options. The NEM is highly emissions intensive by world standards (Garnaut, 2011a), producing in excess of 190 megatonnes (Mt) of greenhouse gas emissions per year. This is the single largest source of emissions in Australia (Ison et al., 2011) and represents around one third of Australia's greenhouse gas emissions. Over the past decade, however, and even with relatively modest renewable energy targets, there has been significant deployment of wind and solar generation.

Recently announced renewable electricity targets for 2050 by Germany (80%) and Denmark (100%) are a bottom-up approach to mitigating greenhouse gas emissions at the national level, simultaneously addressing other objectives such as energy independence (Lilliestam et al., 2012) and competitiveness in clean technology industries (Schreurs, 2012). Although there is a well established body of academic literature going back over a decade evaluating 100% renewable energy scenarios on various geographic scales, more detailed studies are now emerging from government and industry (German Advisory Council on the Environment, 2011; Hand et al., 2012). In Australia, the Federal Government Multi-Party Climate Change Committee (2011) has requested the Australian Energy Market Operator (AEMO) to expand its current planning scenarios to "include further consideration of energy market and transmission planning implications in moving towards 100% renewable energy".

Previous work by the authors has demonstrated the potential technical feasibility of using 100% renewable energy sources to supply current NEM demand while meeting the market's reliability standard in a given year[1] (Elliston et al., 2012b). We simulated a 100% renewable electricity system for one year, using actual hourly demand data and weather observations for 2010. In the simulations, demand is met by electricity generation mixes based on current commercially available renewable energy technologies: wind power, parabolic trough concentrating solar thermal (CST) with thermal

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[1] The NEM reliability standard is currently set at 0.002% unserved energy per year.

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Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time

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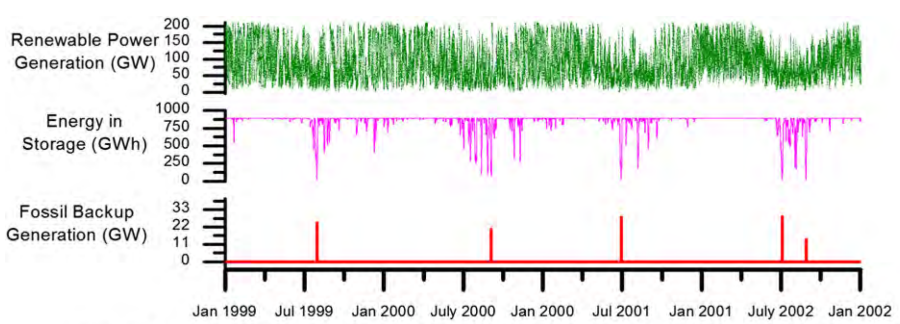
HIGHLIGHTS

- ► We modeled wind, solar, and storage to meet demand for 1/5 of the USA electric grid.
- ► 28 billion combinations of wind, solar and storage were run, seeking least-cost.
- ► Least-cost combinations have excess generation (3× load), thus require less storage.
- ► 99.9% of hours of load can be met by renewables with only 9–72 h of storage.
- ► At 2030 technology costs, 90% of load hours are met at electric costs below today's.

GRAPHICAL ABSTRACT



Load was met with renewable generation and storage 99.9% of hours over 4 years; fossil backup needed on five occasions

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ABSTRACT

We model many combinations of renewable electricity sources (inland wind, offshore wind, and photovoltaics) with electrochemical storage (batteries and fuel cells), incorporated into a large grid system (72 GW). The purpose is twofold: 1) although a single renewable generator at one site produces intermittent power, we seek combinations of diverse renewables at diverse sites, with storage, that are not intermittent and satisfy need a given fraction of hours. And 2) we seek minimal cost, calculating true cost of electricity without subsidies and with inclusion of external costs. Our model evaluated over 28 billion combinations of renewables and storage, each tested over 35,040 h (four years) of load and weather data. We find that the least cost solutions yield seemingly-excessive generation capacity—at times, almost three times the electricity needed to meet electrical load. This is because diverse renewable generation and the excess capacity together meet electric load with less storage, lowering total system cost. At 2030 technology costs and with excess electricity displacing natural gas, we find that the electric system can be powered 90%–99.9% of hours entirely on renewable electricity, at costs comparable to today's—but only if we optimize the mix of generation and storage technologies.

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Simulations of scenarios with 100% renewable electricity in the Australian National Electricity Market

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ABSTRACT

As a part of a program to explore technological options for the transition to a renewable energy future, we present simulations for 100% renewable energy systems to meet actual hourly electricity demand in the five states and one territory spanned by the Australian National Electricity Market (NEM) in 2010. The system is based on commercially available technologies: concentrating solar thermal (CST) power with thermal storage, wind, photovoltaic (PV), existing hydro and biofuelled gas turbines. Hourly solar and wind generation data are derived from satellite observations, weather stations, and actual wind farm outputs. Together CST and PV contribute about half of total annual electrical energy supply.

A range of 100% renewable energy systems for the NEM are found to be technically feasible and meet the NEM reliability standard. The principal challenge is meeting peak demand on winter evenings following overcast days when CST storage is partially charged and sometimes wind speeds are low. The model handles these circumstances by combinations of an increased number of gas turbines and reductions in winter peak demand. There is no need for conventional base-load power plants. The important parameter is the reliability of the whole supply-demand system, not the reliability of particular types of power plants.

1. Introduction

This paper reports on the on-going development of energy system simulations to identify and quantify the challenges of reliably supplying 100% renewable electricity to the five states and one territory spanned by the Australian NEM. The current climate science suggests that developed countries must aggressively reduce greenhouse gas emissions over the next several decades to a point of near-zero emissions by 2050 in order to avoid global warming of more than 2 °C (IPCC, 2007). The International Energy Agency (2011) notes that 80% of the total energy related emissions permissible by 2035 in its 450 parts per million scenario are already 'locked in' by our existing capital stock of energy infrastructure. Continuing development patterns for the next 5 years would then require that all subsequent energy supply be zero carbon.

Today, the NEM produces around one-third of total Australian greenhouse gas emissions, as the system derives around 90% of supply from lignite, bituminous coal and natural gas. If Australia, currently one of the world's highest per capita greenhouse emitters, is to make its fair contribution to such emission reductions then its highly emissions intensive electricity industry must rapidly transition to zero carbon sources (Garnaut, 2011). Given the long life of electricity industry assets, Australian energy and climate policy must therefore now consider the potential for future low emission electricity systems based on rapid deployment of commercially available zero carbon technologies. The only zero carbon 'sources' that are commercially available and seem likely to be able to make large contributions before 2020 in the Australian context are certain renewable energy sources (Department of Resources, Energy and Tourism, 2011) and demand reduction (e.g., through efficient energy use).

Numerous scenario studies have been published that model the potential for countries, regions, and the entire world, to meet 80–100% of end-use energy demand from renewable energy by some future date, typically mid-century. National scenarios exist for Australia (Wright and Hearps, 2010), Ireland (Connolly et al., 2011), New Zealand (Mason et al., 2010), Portugal (Krajačić et al., 2011), Japan (Lehmann, 2003), the United Kingdom (Kemp and Wexler, 2010), Germany (German Advisory Council on the Environment, 2011) and Denmark (Lund and Mathiesen, 2009). More broadly, a regional study has been produced for northern Europe (Sørensen, 2008) and several studies of the global situation have been produced including by Sørensen and Meibom (2000), Jacobson and Delucchi (2011), Delucchi and Jacobson (2011) and WWF (2011). These scenario studies do not typically specify a transition path nor do they share a common methodology for analysis (Nielsen and Karlsson, 2007). However, they are valuable in showing that aggressive reduction in fossil fuel use is possible, and provide a vision of how the future energy system might look.

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Storage and balancing synergies in a fully or highly renewable pan-European power system

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HIGHLIGHTS

- ▶ We model a wind and solar based European power system with storage and balancing.
- ▶ We find that storage needs peaks when average renewable generation matches load.
- ▶ We find strong synergetic effects when combining storage and balancing.
- ▶ We study the effects of a storage capable of storing 6 h average use.
- ▶ We find a realisable fully renewable scenario based on wind, solar and hydro power.

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ABSTRACT

Through a parametric time-series analysis of 8 years of hourly data, we quantify the storage size and balancing energy needs for highly and fully renewable European power systems for different levels and mixes of wind and solar energy. By applying a dispatch strategy that minimizes the balancing energy needs for a given storage size, the interplay between storage and balancing is quantified, providing a hard upper limit on their synergy. An efficient but relatively small storage reduces balancing energy needs significantly due to its influence on intra-day mismatches. Furthermore, we show that combined with a low-efficiency hydrogen storage and a level of balancing equal to what is today provided by storage lakes, it is sufficient to meet the European electricity demand in a fully renewable power system where the average power generation from combined wind and solar exceeds the demand by only a few percent.

1. Introduction

A fully renewable pan-European power system will depend on a large share of non-dispatchable, weather dependent sources, primarily wind and solar power (Czisch, 2005; Jacobson and Delucchi, 2011). The optimal ratio between and necessary amount of wind and solar power depends on storage and balancing resources (Heide et al., 2010, 2011; Hedegaard and Meibom, 2012), transmission (Czisch et al., 2007; Kempton et al., 2010; Schaber et al., 2012a,b), and the characteristics of the climate (Widén, 2011; Aboumahboub et al., 2010) and load (Yao and Steemers, 2005). Based on meteorological data, it was shown that even with unlimited transmission within Europe, a scenario with only wind and solar power in combination with either only storage (Heide et al., 2010) or only balancing (Heide et al., 2011) requires a very large amount of excess generation in order to be technically feasible. Here, we study the intermediate and more realistic scenarios where power generation from the two weather-driven variable renewable energy (VRE) sources is backed up by specific combinations of storage and balancing. We identify a class of realistic and feasible scenarios for building a fully or partially renewable pan-European power system.

The main point of our paper is to outline what is possible in a wind and solar based European power system with storage and balancing systems. The power capacities of the storage and balancing facilities are not determined; this would require a more complex modeling with explicit inclusion of power transmission (Rodriguez et al., 2012). We focus on wind and solar power and assume no bottlenecks in the power grid, employ an optimal storage dispatch strategy and ignore storage charge and discharge capacities and economic aspects. The incentives for doing so are closely related and at least threefold.

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ANALYSIS

The carbon abatement potential of high penetration intermittent renewables†

Elaine K. Hart* and Mark Z. Jacobson

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The carbon abatement potentials of wind turbines, photovoltaics, and concentrating solar power plants were investigated using dispatch simulations over California with 2005–06 meteorological and load data. A parameterization of the simulation results is presented that provides approximations of both low-penetration carbon abatement rates and maximum carbon abatement potentials based on the temporal characteristics of the resource and the load. The results suggest that shallow carbon emissions reductions (up to 20% of the base case) can be achieved most efficiently with geothermal power and demand reductions *via* energy efficiency or conservation. Deep emissions reductions (up to 89% for this closed system), however, may require the build-out of very large fleets of intermittent renewables and improved power system flexibility, communications, and controls. At very high penetrations, combining wind and solar power improved renewable portfolio performance over individual build-out scenarios by reducing curtailment, suggesting that further reductions may be met by importing uncorrelated out-of-state renewable power. The results also suggest that 90–100% carbon emission reductions will rely on the development of demand response and energy storage facilities with power capacities of at least 65% of peak demand and energy capacities large enough to accommodate seasonal energy storage.

1 Introduction

In response to a growing concern over global warming, the last decade has seen a surge in proposals for reducing the carbon dioxide emissions associated with electric power generation, many of which include large build-outs of renewable technologies including wind, photovoltaics (PVs), concentrating solar power (CSP), geothermal, wave, and tidal power. This paper seeks to determine how the temporal characteristics of electric power demand, the variability of renewable resources, and the controls employed by renewable technologies influence the potential for a renewable portfolio to displace carbon-based generation and to reduce carbon dioxide emissions at very high penetrations. Furthermore, we seek to understand which of these factors has the strongest influence on the carbon abatement potential of a given technology, and in the case that a limit to the carbon abatement potential of intermittent renewables exists, what technologies are needed to achieve complete decarbonization of the electricity grid.

In the past, economic analyses of the carbon abatement potential of renewables have tended to assume that renewable

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Broader context

The reliable integration of renewable resources on to the electricity grid represents an important step toward decarbonizing the electric power sector and mitigating global climate change. This step is complicated by both the variability and the uncertainty associated with power output from renewable resources, like wind and solar power. Analyses that seek to quantify system reliability, reserve requirements, and the carbon dioxide emissions associated with operating these reserves have historically relied on simulations with high temporal resolution (typically an hour or less) and with stochastic treatments, both of which increase the computational complexity significantly. However, energy-economic models capable of analyzing the costs and economic impacts of different decarbonization strategies or policies typically use time scales of one year and cannot accurately resolve the phenomena associated with intermittent renewables. In this paper, we develop a parameterization of the results from higher temporal resolution simulations that can be implemented in large-scale energy-economic models. This effort contributes to the improved economic treatment of renewable power sources in analyses used by policymakers and may provide additional insight regarding technological cost targets for innovators.

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A Monte Carlo approach to generator portfolio planning and carbon emissions assessments of systems with large penetrations of variable renewables

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A B S T R A C T

A new generator portfolio planning model is described that is capable of quantifying the carbon emissions associated with systems that include very high penetrations of variable renewables. The model combines a deterministic renewable portfolio planning module with a Monte Carlo simulation of system operation that determines the expected least-cost dispatch from each technology, the necessary reserve capacity, and the expected carbon emissions at each hour. Each system is designed to meet a maximum loss of load expectation requirement of 1 day in 10 years. The present study includes wind, centralized solar thermal, and rooftop photovoltaics, as well as hydroelectric, geothermal, and natural gas plants. The portfolios produced by the model take advantage of the aggregation of variable generators at multiple geographically disperse sites and the incorporation of meteorological and load forecasts. Results are presented from a model run of the continuous two-year period, 2005–2006 in the California ISO operating area. A low-carbon portfolio is produced for this system that is capable of achieving an 80% reduction in electric power sector carbon emissions from 2005 levels and supplying over 99% of the annual delivered load with non-carbon sources. A portfolio is also built for a projected 2050 system, which is capable of providing 96% of the delivered electricity from non-carbon sources, despite a projected doubling of the 2005 system peak load. The results suggest that further reductions in carbon emissions may be achieved with emerging technologies that can reliably provide large capacities without necessarily providing positive net annual energy generation. These technologies may include demand response, vehicle-to-grid systems, and large-scale energy storage.

1. Introduction

In the United States, approximately 40% of the total annual carbon dioxide emissions are associated with the generation of electricity [1]. Significant reductions in carbon emissions within the United States will therefore require a dramatic shift in the composition of the electric power sector. Several technologies already exist to replace generation from coal and natural gas with cleaner alternatives, but the variability and uncertainty in many renewable resources is anticipated to pose political, financial, and technological challenges to large-scale grid integration. Without practical examples of large systems with very high penetrations of variable generation, models must be employed to predict the behavior of these systems. To date, most grid integration models have focused on wind power, though some have included solar technologies. An extensive review of wind power integration studies across Europe can be found in [2] and a review of current energy system modeling tools can be found in [3].

Early attempts at modeling grid integration of variable generation were based on load duration curve analyses, similar to those used for portfolios of conventional generators [4–6]. More recently, however, grid integration has been formulated primarily as an optimization problem with load balance constraints over multiple time steps. Deterministic load balance models have been used to develop scenarios with high penetrations of wind power within different types of preexisting generation portfolios [7], to study the affects of aggregating multiple geographically disperse wind farms [8], and to analyze the operational costs associated with intrahour fluctuations of wind power output [9]. Other grid integration studies have explored how the complementary nature of different renewable energy resources (including wind, solar, wave, geothermal, and/or hydroelectric power) can be used to best match a time-varying power demand [10–16].

The stochastic nature of wind and solar complicates the treatment of system reliability in grid integration studies. Probabilistic models are already used to account for forced outages of

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100% Renewable energy systems, climate mitigation and economic growth

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ABSTRACT

Greenhouse gas mitigation strategies are generally considered costly with world leaders often engaging in debate concerning the costs of mitigation and the distribution of these costs between different countries. In this paper, the analyses and results of the design of a 100% renewable energy system by the year 2050 are presented for a complete energy system including transport. Two short-term transition target years in the process towards this goal are analysed for 2015 and 2030. The energy systems are analysed and designed with hour-by-hour energy system analyses. The analyses reveal that implementing energy savings, renewable energy and more efficient conversion technologies can have positive socio-economic effects, create employment and potentially lead to large earnings on exports. If externalities such as health effects are included, even more benefits can be expected. 100% Renewable energy systems will be technically possible in the future, and may even be economically beneficial compared to the business-as-usual energy system. Hence, the current debate between leaders should reflect a combination of these two main challenges.

1. Introduction

If temperature increases are to be held between 2 and 2.4 °C, the concentration of CO_2 equivalents in the atmosphere should be kept below between 445 and 490 ppm, according to the most recent report from the United Nations Intergovernmental Panel on Climate Change from 2007, IPCC Fourth Assessment Report: Climate Change 2007 (AR4) [1]. As the concentration of greenhouse gases has already reached about 450 ppm CO_2 equivalents in 2005, the IPCC has estimated that the discharge of greenhouse gases must peak as soon as possible, no later than the year 2015. Furthermore, the discharge of greenhouse gases must be reduced by 50–85% by 2050 compared with the year 2000. These reductions should lie closer to 85% than 50% to ensure a maximum of 2 °C increase. It is estimated that discharges per person must be reduced to between 0.8 and 2.5 tonnes of CO_2 equivalents per person per year.

Even with a 2 °C increase, significant changes in the climates of individual regions and the world at large are inevitable. However, it can be ensured that climate change does not accelerate beyond the point where the effects become self-reinforcing. In August 2009, the concentration of CO_2 in the atmosphere was 387 ppm [2]. The 2 °C increase estimate was based on a reduction to 350–400 ppm CO_2 in the atmosphere. However, the latest IPCC report from 2007 is based on data from 2005, and the latest results found by James Hansen from NASA, among others, indicate that this level is no longer sufficient. The most recent observations and model calculations show that a reduction to 350 ppm CO_2 in the atmosphere may be necessary, or even that anthropologically emitted climate gases must be avoided entirely in order to avoid irreparable damage [3–5]. In August 2009, the Chairman of the IPCC, recognised this point and stated that he now supports a 350 ppm CO_2 maximum instead of the 450 ppm in AR4 from 2007.

In the USA, the European Union and China, among others, policies have been formulated with the objective of decreasing emissions. And in many nations around the world, policies to raise the share of renewable energy are being initiated as part of the global response to climate change. The major debate occurring in many countries is mostly concerned with the costs of mitigating greenhouse gases.

Often, the debate about measures to mitigate greenhouse gases between world leaders is intertwined with other issues. These issues reflect the current geopolitical situation, the current interdependency between countries in the demand and supply of energy products, or issues regarding the negotiations between developed and developing countries in e.g. the World Trade Organisation (WTO). While costs have always been a central issue in the climate debate, as well as concerns regarding human equality. Recently, since the Poznan COP14 conference and the Copenhagen Accord from the COP15, the debate on costs and on transactions between developed and undeveloped countries has also reflected the international financial crisis. Developing countries have used the situation to emphasise the need for further aid and support. Also some

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The first step towards a 100% renewable energy-system for Ireland

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Ireland

ABSTRACT

In 2007 Ireland supplied 96% of the total energy demand with fossil fuels (7% domestic and 89% imported) and 3% with renewable energy, even though there are enough renewable resources to supply all the energy required. As energy prices increase and the effects of global warming worsen, it is essential that Ireland begins to utilise its renewable resources more effectively. Therefore, this study presents the first step towards a 100% renewable energy-system for Ireland. The energy-system analysis tool used was EnergyPLAN, as it accounts for all sectors of the energy-system that need to be considered when integrating large penetrations of renewable energy: the electricity, heat, and transport sectors. Initially, a reference model of the existing Irish energy-system was constructed, and subsequently three different 100% renewable energy-systems were created with each focusing on a different resource: biomass, hydrogen, and electricity. These energy-systems were compared so that the benefits from each could be used to create an 'optimum' scenario called combination. Although the results illustrate a potential 100% renewable energy-system for Ireland, they have been obtained based on numerous assumptions. Therefore, these will need to be improved in the future before a serious roadmap can be defined for Ireland's renewable energy transition.

1. Introduction

On a global scale in recent years the affects of climate have become more apparent, new fossil fuel reserves have become scarce, and energy prices have reached all-time highs. Meanwhile in Ireland,[1] approximately 93% of the energy used for electricity generation in Ireland is fossil-fuel based, with 59% of this energy wasted due to transformation losses [1]. Also, approximately 89% of the total fuel consumed in Ireland is imported, which is an extremely volatile situation in the current economic climate [1]. In contrast to fossil fuels, Ireland has an abundant renewable energy resource [2,3] and hence under European Commission regulations, Ireland must supply 16% of the total energy requirement from renewable resources by 2020 [4]. With this in mind, it is essential that Ireland identifies the most effective transition from a fossil-fuel to a renewable energy-system (RES). Therefore, the aim of this work is to evaluate how Ireland can make this transition to a RES. Also, as the Irish energy-system is very similar to those that exist in most developed countries [5], the results obtained in this investigation reflect the changes necessary in a number of other energy-systems also. In addition, the Irish energy-system is an excellent laboratory for experimenting with new technologies as it is a relatively small country with 4.4 million people, it is an island which makes it specifically attractive for the implementation of alternative transport technologies such electric vehicles, and it has an abundant resource of renewable energy in the form of wind, wave, tidal, solar and biomass [2,3].

To date, a number of analyses have been carried out on the feasibility of integrating renewable energy onto the Irish electric grid. In 2003, Gardner et al. [6] investigated the effects of more wind energy on the electricity grid in Ireland and Northern Ireland, concluding that there is no technical limit on the wind penetration feasible, but instead costs are the limiting factor. Therefore, Garner et al. identified the most costly aspects of increasing the wind penetration as transmission reinforcement, wind curtailment, capital costs and operating costs. In 2004, ESB National Grid [7] also analysed the costs associated with increasing the wind penetration in Ireland, but in addition this report also investigated the effects of large wind-penetrations on conventional generation. The report concluded that increasing the wind penetration in Ireland from 0% to 11.7% would increase the total generation costs by €196 million, and would minimally affect baseload plant. However, peaking and mid-merit power plants would be affected as the wind penetration increases due to their more frequent start-ups, increased ramping, and lower capacity factors. Finally, in 2007, Meibom et al. [8] modelled the Irish electricity grid using the WILMAR energy tool [9]. The objective was to identify the effects of large wind-penetrations on the island of Ireland in relation to overall

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[1] Ireland refers to the Republic of Ireland only unless otherwise specified.

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A 100% renewable electricity generation system for New Zealand utilising hydro, wind, geothermal and biomass resources

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ABSTRACT

The New Zealand electricity generation system is dominated by hydro generation at approximately 60% of installed capacity between 2005 and 2007, augmented with approximately 32% fossil-fuelled generation, plus minor contributions from geothermal, wind and biomass resources. In order to explore the potential for a 100% renewable electricity generation system with substantially increased levels of wind penetration, fossil-fuelled electricity production was removed from an historic 3-year data set, and replaced by modelled electricity production from wind, geothermal and additional peaking options. Generation mixes comprising 53–60% hydro, 22–25% wind, 12–14% geothermal, 1% biomass and 0–12% additional peaking generation were found to be feasible on an energy and power basis, whilst maintaining net hydro storage. Wind capacity credits ranged from 47% to 105% depending upon the incorporation of demand management, and the manner of operation of the hydro system. Wind spillage was minimised, however, a degree of residual spillage was considered to be an inevitable part of incorporating non-dispatchable generation into a stand-alone grid system. Load shifting was shown to have considerable advantages over installation of new peaking plant. Application of the approach applied in this research to countries with different energy resource mixes is discussed, and options for further research are outlined.

1. Introduction

Increased reliance on electricity generation from renewable resources is a key and urgently required strategy for reducing anthropogenic greenhouse gas (GHG) emissions worldwide. High per capita emitting countries like New Zealand have been signalled to require 20–40% emissions reductions by 2020, rising to 80–90% by 2050, based on global equity considerations e.g. Stern (2008), although the New Zealand government has since committed to a lesser target of 10–20% reduction on 1990 levels by 2020 (NZ Government, 2009). As the combustion of fossil fuels for electricity generation accounted for approximately 22% of total global GHG emissions (10.5 Gt-CO_2) in 2002 (IPCC, 2005, 2007) and is rising, the displacement of fossil fuel emissions in the global electricity sector is an essential goal. Furthermore, emissions from transport at 13.1% of total global GHG emissions in 2004 (IPCC, 2007), are also significant. The New Zealand electricity and heat sector generated 8.8% of total emissions in 2007, and transport contributed 19.9% of total emissions (MfE, 2009). Given the attraction from an energetics point of view of long-term electrification of transport e.g. Lund and Kempton (2008), renewable electricity systems offer a timely, long-term and potentially sustainable pathway for substantially reducing GHG emissions across these two important sectors. System level efficiencies for electrical energy chains are significantly better than those for liquid fuel to propulsion energy chains e.g. Page and Krumdieck (2009) hence overall energy efficiency gains will arise from such a transition. Whilst continued use of fossil fuels for electricity generation in combination with carbon capture and storage (CCS) has been widely touted as a potential solution, and recently incorporated in the UK low carbon economy transition plan (UK Government, 2009), serious questions have been raised concerning the energy penalty, long-term storage risks and potential timeliness of this technology both globally, and for New Zealand (Page et al., 2008, 2009). Furthermore CCS is not applicable to mobile emissions sources such as motor vehicles.

In New Zealand, hydro generation has historically been, and remains, the dominant form of installed electricity generation capacity (Fig. 1). Hydro provided 55% of electricity production in 2007 (Fig. 2), of which 74% was generated in the South Island (MED, 2008). The majority of demand is located in the North

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Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050

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ABSTRACT

This paper presents the methodology and results of the overall energy system analysis of a 100% renewable energy system. The input for the systems is the result of a project of the Danish Association of Engineers, in which 1600 participants during more than 40 seminars discussed and designed a model for the future energy system of Denmark. The energy system analysis methodology includes hour by hour computer simulations leading to the design of flexible energy systems with the ability to balance the electricity supply and demand. The results are detailed system designs and energy balances for two energy target years: year 2050 with 100% renewable energy from biomass and combinations of wind, wave and solar power; and year 2030 with 50% renewable energy, emphasising the first important steps on the way. The conclusion is that a 100% renewable energy supply based on domestic resources is physically possible, and that the first step towards 2030 is feasible to Danish society. However, Denmark will have to consider to which degree the country shall rely mostly on biomass resources, which will involve the reorganisation of the present use of farming areas, or mostly on wind power, which will involve a large share of hydrogen or similar energy carriers leading to certain inefficiencies in the system design.

1. Introduction

In a recent report from 2007, the United Nations' International Panel of Climate Change, IPCC, emphasises the many indicators on climate change and recommends that the world society respond to the serious problems. In the US, the European Union and China, policies have been formulated with the objective of decreasing CO_2 emissions. And in many nations around the world, policies to raise the share of renewable energy are being initiated as part of the global response to climate change [1–10]. In March 2007, the European Union defined a target of 20% renewable energy for year 2020. In Denmark, a target of 30% renewable energy for year 2025 has just been proposed by the Danish Government.

In Denmark, on the one hand, CO_2 emissions per capita have for many years been among the highest in the world on the other, an active energy policy has already led to remarkable results in the decrease of emissions [11]. For a period of 35 years, Denmark has managed to stabilise the primary energy supply, which is the same today as it was before the first oil crises in the early 70s. Furthermore, the share of oil is much smaller today. 20% of the electricity is supplied by wind power and 15% of the primary energy supply is renewable energy including biomass and waste incineration. Moreover, savings and efficiency measures have constituted an important part of the policy, leading to a situation today in which 50% of the electricity is produced by combined heat and power (CHP).

In his opening speech to the Danish Parliament in October 2006, the Prime Minister announced the long-term target of Denmark: 100% independency of fossil fuels and nuclear power. A few months later, the Danish Association of Engineers (IDA) put forward a proposal on how and when to achieve such targets. This proposal was the result of the "Energy Year 2006", in which 1600 participants during more than 40 seminars discussed and designed a model for the future energy system of Denmark, putting emphasis on energy efficiency, CO_2 reduction, and industrial development. The proposal was presented as the IDA Energy Plan 2030 (see Fig. 1).

The design of 100% renewable energy systems involves at least three major technological changes [12]: energy savings on the demand side [13,14], efficiency improvements in the energy production [15,16], and the replacement of fossil fuels by various sources of renewable energy [17,18]. Consequently, large-scale renewable energy implementation plans must include strategies for integrating renewable sources in coherent energy systems influenced by energy savings and efficiency measures [19–26].

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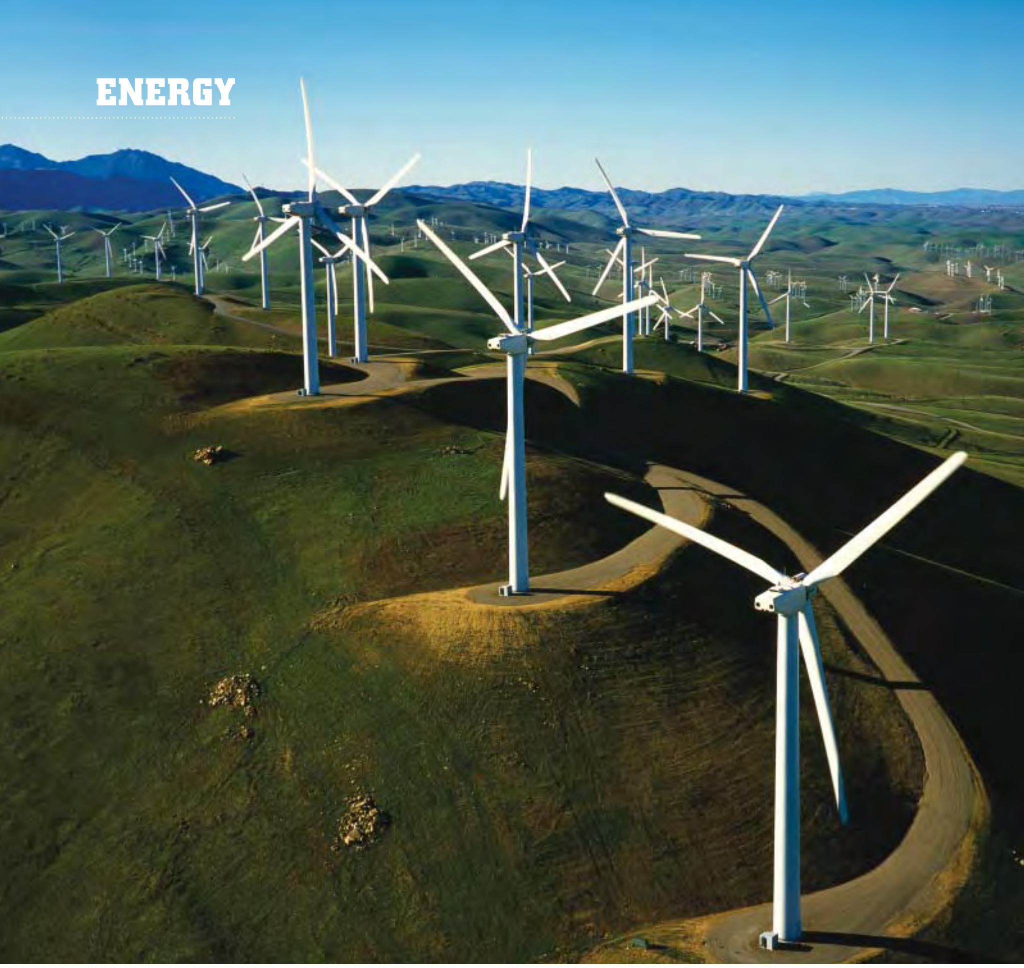

A PATH TO SUSTAINABLE ENERGY BY 2030

Wind, water and solar technologies can provide 100 percent of the world's energy, eliminating all fossil fuels. HERE'S HOW

By Mark Z. Jacobson and Mark A. Delucchi

In December leaders from around the world will meet in Copenhagen to try to agree on cutting back greenhouse gas emissions for decades to come. The most effective step to implement that goal would be a massive shift away from fossil fuels to clean, renewable energy sources. If leaders can have confidence that such a transformation is possible, they might commit to an historic agreement. We think they can.

A year ago former vice president Al Gore threw down a gauntlet: to repower America with 100 percent carbon-free electricity within 10 years. As the two of us started to evaluate the feasibility of such a change, we took on an even larger challenge: to determine how 100 percent of the world's energy, for *all* purposes, could be supplied by wind, water and solar resources, by as early as 2030. Our plan is presented here.

Scientists have been building to this moment for at least a decade, analyzing various pieces of the challenge. Most recently, a 2009 Stanford University study ranked energy systems according to their impacts on global warming, pollution, water supply, land use, wildlife and other concerns. The very best options were wind, solar, geothermal, tidal and hydroelectric power—all of which are driven by wind, water or sunlight (referred to as WWS). Nuclear power, coal with carbon capture, and ethanol were all poorer options, as were oil and natural gas. The study also found that battery-electric vehicles and hydrogen fuel-cell vehicles recharged by WWS options would largely eliminate pollution from the transportation sector.

Our plan calls for millions of wind turbines, water machines and solar installations. The numbers are large, but the scale is not an insurmountable hurdle; society has achieved massive

JOHN LEE *Aurora Photos (wind farm)*; BILL HEINSOHN *Aurora Photos (dam)*

Realisable Scenarios for a Future Electricity Supply based 100% on Renewable Energies

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Abstract

In view of the resource and climate problems, it seems obvious that we must transform our energy system into one using only renewable energies. But questions arise how such a system should be structured, which techniques should be used and, of course, how costly it might be. These questions were the focus of a study which investigated the cost optimum of a future renewable electricity supply for Europe and its closer Asian and African neighbourhood. The resulting scenarios are based on a broad data basis of the electricity consumption and for renewable energies. A linear optimisation determines the best system configuration and temporal dispatch of all components. The outcome of the scenarios can be considered as being a scientific breakthrough since it proves that a totally renewable electricity supply is possible even with current technology and at the same time is affordable for our national economies. In the conservative base case scenario, wind power would dominate the production spread over the better wind areas within the whole supply area, connected with the demand centres via HVDC transmission. The transmission system, furthermore, powerfully integrates the existing storage hydropower to provide for backup coequally assisted by biomass power and supported by solar thermal electricity. The main results of the different scenarios can be summarized as follows:

- A totally renewable electricity supply for Europe and its neighbourhood is possible and affordable.
- Electricity import from non-European neighbour countries can be a very valuable and substantial component of a future supply.
- Smoothing effects by the use of sources at locations in different climate zones improve the security of the supply and reduce the costs.
- A large-scale co-operation of many different countries opens up for the possibility to combine the goals of development policy and climate politics in a multilateral win-win strategy.

To aid implementation, an international extension of the ideas of the German energy feed law (or similar other schemes around the world) is proposed for the follow-up treaty to the Kyoto climate accord.

1 Introduction

At the first Risø Energy Conference in 2003 [GiebelEtAl 2003] we have shown that the large-scale transport of renewable energy, in particular wind energy, via HVDC (High-Voltage Direct Current) is possible from some wind-rich regions around Europe to the centre of Europe with reasonable cost and with large development benefits for the installing countries. At the second Risø Energy Conference in 2005 [GiebelEtAl 2005] we presented calculations showing that due to the large differences in resources, it can be cheaper to use better wind resources further away (in this case, Egypt) than to use just

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Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply

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Abstract

This article presents the results of analyses of large-scale integration of wind power, photo voltaic (PV) and wave power into a Danish reference energy system. The possibility of integrating Renewable Energy Sources (RES) into the electricity supply is expressed in terms of the ability to avoid excess electricity production. The different sources are analysed in the range of an electricity production from 0 to 100% of the electricity demand. The excess production is found from detailed energy system analyses on the computer model EnergyPLAN. The analyses have taken into account that certain ancillary services are needed in order to secure the electricity supply system.

The idea is to benefit from the different patterns in the fluctuations of different renewable sources. And the purpose is to identify optimal mixtures from a technical point of view. The optimal mixture seems to be when onshore wind power produces approximately 50% of the total electricity production from RES. Meanwhile, the mixture between PV and wave power seems to depend on the total amount of electricity production from RES. When the total RES input is below 20% of demand, PV should cover 40% and wave power only 10%. When the total input is above 80% of demand, PV should cover 20% and wave power 30%. Meanwhile the combination of different sources is alone far from a solution to large-scale integration of fluctuating resources. This measure is to be seen in combination with other measures such as investment in flexible energy supply and demand systems and the integration of the transport sector.

Keywords: Wind power; Wave power; Photo voltaic; Energy system analysis; Distributed generation; Renewable energy; Energy modelling

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Switching to a U.S. hydrogen fuel cell vehicle fleet: The resultant change in emissions, energy use, and greenhouse gases

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Abstract

This study examines the potential change in primary emissions and energy use from replacing the current U.S. fleet of fossil-fuel on-road vehicles (FFOV) with hybrid electric fossil fuel vehicles or hydrogen fuel cell vehicles (HFCV). Emissions and energy usage are analyzed for three different HFCV scenarios, with hydrogen produced from: (1) steam reforming of natural gas, (2) electrolysis powered by wind energy, and (3) coal gasification. With the U.S. EPA's National Emission Inventory as the baseline, other emission inventories are created using a life cycle assessment (LCA) of alternative fuel supply chains. For a range of reasonable HFCV efficiencies and methods of producing hydrogen, we find that the replacement of FFOV with HFCV significantly reduces emission associated with air pollution, compared even with a switch to hybrids. All HFCV scenarios decrease net air pollution emission, including nitrogen oxides, volatile organic compounds, particulate matter, ammonia, and carbon monoxide. These reductions are achieved with hydrogen production from either a fossil fuel source such as natural gas or a renewable source such as wind. Furthermore, replacing FFOV with hybrids or HFCV with hydrogen derived from natural gas, wind or coal may reduce the global warming impact of greenhouse gases and particles (measured in carbon dioxide equivalent emission) by 6, 14, 23, and 1%, respectively. Finally, even if HFCV are fueled by a fossil fuel such as natural gas, if no carbon is sequestered during hydrogen production, and 1% of methane in the feedstock gas is leaked to the environment, natural gas HFCV still may achieve a significant reduction in greenhouse gas and air pollution emission over FFOV.

Keywords: Hydrogen fuel cell vehicle; Life cycle assessment; Air pollution; Coal gasification; Steam reforming; Wind electrolysis

1. Introduction

The purpose of this analysis is to study the potential effects on air pollution and global climate of replacing fossil-fuel on-road vehicles (FFOV) with those powered by hydrogen fuel cells, where the hydrogen is produced from: (1) steam reforming of natural gas, (2) wind-powered electrolysis, or (3) coal gasification. The present paper conducts a well-to-wheels analysis for different hydrogen fuel cell vehicle (HFCV) scenarios and determines the net changes in primary emissions and energy use that result. The emission results from this study serve as inputs into a second study, which examines the effect of these emission changes on ambient air pollution and on potential health and climate costs [1]. The complete research effort is published in two parts in these two separate papers.

This paper combines a life cycle assessment (LCA) with data from the U.S. Environmental Protection Agency's (EPA's) National Emission Inventory (NEI) [2] to estimate the net change in emission upon a switch to a hybrid FFOV or a HFCV fleet. We evaluate one hybrid FFOV scenario and three HFCV scenarios in which hydrogen is produced by: (1) decentralized steam reforming of natural gas, (2) decentralized electrolysis powered by wind turbines, and (3) centralized coal gasification [3]. We conduct a LCA of different HFCV scenarios to evaluate the primary energy and pollutant flows involved in fossil fuel and hydrogen scenarios

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observed rates. Comparisons at regional to continental scales also show that mean snow accumulation from meteorological models is very low over most of the interior of the Antarctic continent. For example, basin-averaged, model-simulated, mean-annual snow accumulation compared with regional accumulation estimates compiled from in situ and passive microwave measurements (*19*) ranged from 25 to 50% for primarily interior basins (e.g., J″-K and B-C).

It is clear, therefore, that the ERA-40 reanalysis and ECMWF operational analyses used here capture much of the relative temporal variability in accumulation while underestimating the total amount, resulting in underestimation of the magnitude of modeled temporal trends in snowfall rate. Although some of the difference between observed elevation change and modeled snowfall-rate trends likely results from changes in snow densification in response to changing snow accumulation rate and temperature (*20*), most of the difference probably results from underestimation of the magnitude of annual-to-decadal changes in snowfall by the meteorological models.

Placing these results in perspective, a sea-level change of 1 mm/year corresponds to 360 billion metric tons of water per year (*21*). Using a near-surface snow density of 350 kg/m^3, an average elevation change of 1.8 ± 0.3 cm/year over an area of 7.1 million km^2 for the East Antarctic interior (table S1) corresponds to a mass gain of 45 ± 7 billion metric tons of water per year and a corresponding sea-level drop of 0.12 ± 0.02 mm/year. We believe that this is a conservative estimate. The spatially uniform and positive dH/dt values for the East Antarctic interior (Fig. 2) suggest that much of the area south of the East Antarctic ROC may also be thickening. These results are consistent with ice-core evidence, though sparse, for increasing accumulation in East Antarctica during the decades preceding our observational time period (*22–26*). Thus, we cannot rule out a longer-term mass imbalance due to increased precipitation, as predicted by earlier studies [e.g., (*27*, *28*)] and the most recent IPCC assessment (*6*).

The vast size of the East Antarctic ice sheet means that even a small imbalance has a large effect on sea-level change. For example, a 1.8 cm/year average dH/dt over the entire East Antarctic ice sheet (~10 million km^2) would correspond to a sea-level drop of 0.18 mm/year (assuming a recent change and snow density of 350 kg/m^3), nearly as large as the most recent estimate of 0.20 mm/year (*2*) for the Greenland ice sheet's contribution to sea-level rise, and larger than the most recent estimate for the West Antarctic ice sheet's contribution of 0.16 mm/year (*3*).

Our results show that the East Antarctic ice-sheet interior increased in overall thickness within the ROC from 1992 to 2003 and that this increase is probably the result of increased snowfall. Both of these observations are consistent with the latest IPCC prediction for Antarctica's likely response to a warming global climate (*6*). However, the IPCC prediction does not consider possible dynamic changes in coastal areas of the ice sheet. Moreover, these results have only sparse coverage of the coastal areas where recent dynamic changes may be occurring (*4*). Thus, the overall contribution of the Antarctic ice sheet to global sea-level change will depend on the balance between mass changes on the interior and those in coastal areas.

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Materials and Methods
Figs. S1 to S4
Table S1
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Cleaning the Air and Improving Health with Hydrogen Fuel-Cell Vehicles

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Converting all U.S. onroad vehicles to hydrogen fuel-cell vehicles (HFCVs) may improve air quality, health, and climate significantly, whether the hydrogen is produced by steam reforming of natural gas, wind electrolysis, or coal gasification. Most benefits would result from eliminating current vehicle exhaust. Wind and natural gas HFCVs offer the greatest potential health benefits and could save 3700 to 6400 U.S. lives annually. Wind HFCVs should benefit climate most. An all-HFCV fleet would hardly affect tropospheric water vapor concentrations. Conversion to coal HFCVs may improve health but would damage climate more than fossil/electric hybrids. The real cost of hydrogen from wind electrolysis may be below that of U.S. gasoline.

Switching from a fossil-fuel economy to a hydrogen economy would be subject to technological hurdles, the difficulty of creating a new energy infrastructure, and considerable conversion costs (*1*) but could provide health, environmental, climate, and economic benefits and reduce reliance on diminishing oil supplies. Although studies have modeled the effects of hydrogen leakage or reduced emission on global tropospheric and stratospheric chemistry (*2–4*), no study has examined the effect on urban pollution or health of establishing a hydrogen economy. Furthermore, no study has examined the likely effects of this switch on aerosol particles (which have a large impact on climate and are the deadliest components