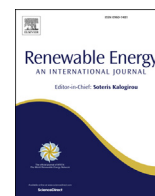


**Abstracts of 42 Peer-Reviewed Published  
Journal Articles From 12 Independent  
Research Groups With 77 Different  
Authors Supporting the Result That  
Energy for Electricity, Transportation,  
Building Heating/Cooling, and/or  
Industry can be Supplied Reliably  
with 100% or Near-100% Renewable  
Energy at Difference Locations  
Worldwide**

**April 8, 2019**



# 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.

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## 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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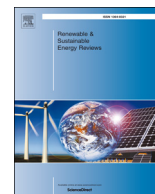
OPEN

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



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## ARTICLE INFO

### Keywords:

100% Renewable energy systems  
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Energy potentials

## 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<sub>2</sub>-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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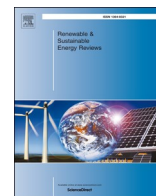
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# Analysing the feasibility of powering the Americas with renewable energy and inter-regional grid interconnections by 2030

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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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## Article

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

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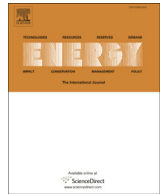
**Abstract:** A 100% renewable energy (RE) scenario featuring high participation in vehicle-to-grid (V2G) services was developed for the Åland islands for 2030 using the EnergyPLAN modelling tool. Hourly data was analysed to determine the roles of various energy storage solutions, notably V2G connections 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<sub>e</sub>) resulted in less gas storage (1200 MWh<sub>th</sub>), electrolyser capacity (6.1 MW<sub>e</sub>), methanation capacity (3.9 MWh<sub>gas</sub>), and offshore wind power capacity (55 MW<sub>e</sub>) 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.



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

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## ABSTRACT

Rapid economic growth in China has led 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%.

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## 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: Smoothing 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.

## ARTICLE INFO

### Keywords:

Renewable energy  
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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 11<sup>th</sup> 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 plant, 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 Inskai*, 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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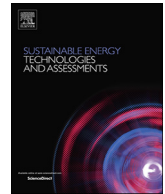
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# Long-term effects of 100% renewable generation on the Colombian power market

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## ARTICLE INFO

### Keywords:

Renewable energy  
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Complementarity  
Simulation

## 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

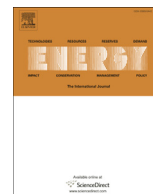
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# Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050

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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  $2.8 \cdot 10^{11} \text{ m}^3$  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.

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## 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].

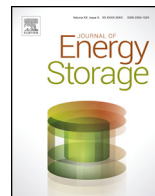
Pakistan with more than 188 million inhabitants stands as the sixth most populous country in the world (2013). Traditionally, Pakistan was an agrarian economy, but over the time, industry and services sector have become main contributors to the GDP [3]. Presently energy production and consumption in 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.

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## 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<sub>2</sub> 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

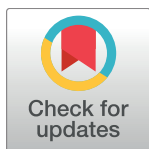
RESEARCH ARTICLE

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

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**Data Availability Statement:** All relevant data are within the paper and its Supporting Information files.

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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<sup>3</sup> of water desalination and 640 TWh<sub>LHV</sub> 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<sub>LHV</sub> and 0.91 €/m<sup>3</sup>, 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



## 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



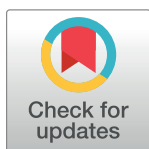
RESEARCH ARTICLE

# 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.

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## 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

## 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 concrete 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

## 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<sub>el</sub> in a decentralized case and 42 €/MWh<sub>el</sub> 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



# 100% renewable electricity in Australia

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## ABSTRACT

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.

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## 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.

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## 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 CO<sub>2</sub>-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

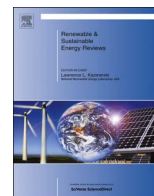
adopted by the Australian Capital Territory (ACT) Government to achieve its early GHG target of 100% renewable electricity by 2020 [4]. Wind and photovoltaics (PV) systems constitute virtually all new generation systems in Australia now and for the foreseeable future. Over the last decade, wind power 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

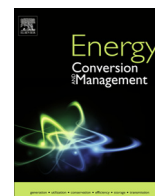
This study presents one scenario for a 100% renewable energy system in Europe by the year 2050. The transition from a business-as-usual situation in 2050, to a 100% renewable energy Europe is analysed in a series of steps. Each step reflects one major technological change. For each step, the impact is 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 constraints. 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<sub>h</sub> of heat on a cost competitive level of 84 €/MW<sub>h<sub>el</sub></sub> 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<sub>h<sub>el</sub></sub>, 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<sub>h<sub>el</sub></sub>. 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.

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## 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

**W**orldwide, 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<sub>2</sub>); 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<sub>2</sub> (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.

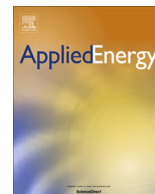
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## Smart Energy Systems for coherent 100% renewable energy and transport solutions



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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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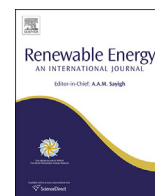
### ABSTRACT

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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Low carbon scenarios

## ABSTRACT

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<sub>2</sub> 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.

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## 1. Introduction

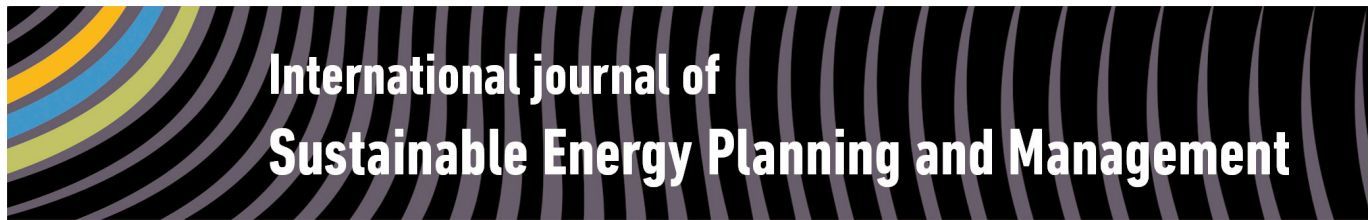
There is a growing recognition of the urgency for large, rapid and sustained emissions reductions to avoid dangerous global warming. Achieving deep cuts to greenhouse gas emissions in some sectors (e.g., transportation, agriculture) is likely to be more difficult than the electricity sector. The Australian 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.

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### Keywords:

100% renewable energy;  
smart energy system;  
Ireland;  
technical analyses;  
economic analyses;  
wind power;  
job creation;

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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  $40 \times 40 \text{ km}^2$ , 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.

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## 1. Introduction

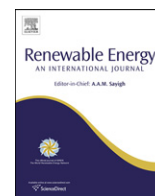
$\text{CO}_2$  and air pollution emission reduction goals as well as energy security, price stability, and affordability considerations make renewable electricity generation attractive. A highly renewable electricity supply will be based to a large extent on wind and solar photovoltaic (PV) power, since 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  $3000 \times 500 \text{ km}^2$ ), discussed in Ref. [8], to Denmark (about  $200 \times 300 \text{ km}^2$ ), 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  $40 \times 40 \text{ km}^2$ , 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.

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### 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.

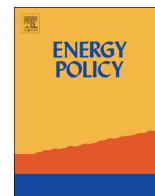
The interesting question about the backup system is thus rather how much energy the backup power plants have to provide – and how this depends on grid extensions and novel storage capacities. Grids and storage help to reduce backup energy demand by averaging intermittent power generation in space and 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<sub>2</sub> 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<sub>2</sub> 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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Least cost

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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.

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## 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<sup>1</sup> (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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<sup>1</sup> The NEM reliability standard is currently set at 0.002% unserved energy per year.



# 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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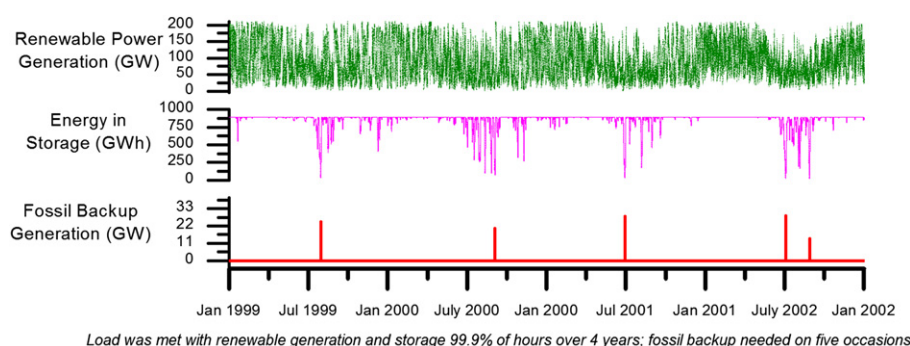
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## HIGHLIGHTS

- 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 ( $3\times$  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



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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.

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## 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.

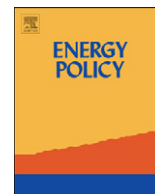
Today, the NEM produces around one-third of total Australian greenhouse gas emissions, as the system derives around 90% of supply from lignite, bituminous coal and natural gas. If Australia, currently one of the world's highest per capita greenhouse emitters, is to make its fair contribution to such 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.

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## 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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## The carbon abatement potential of high penetration intermittent renewables†

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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.

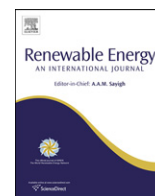
In the past, economic analyses of the carbon abatement potential of renewables have tended to assume that renewable

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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.



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

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## ABSTRACT

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.

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## 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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Socio-economics

Job creation

## 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.

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## 1. Introduction

If temperature increases are to be held between 2 and 2.4 °C, the concentration of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> in the atmosphere was 387 ppm [2]. The 2 °C increase estimate was based on a reduction to 350–400 ppm CO<sub>2</sub> in the atmosphere. However, the latest IPCC report from 2007 is based on data from 2005, and the latest results found

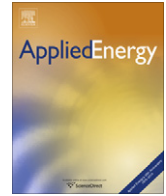
by James Hansen from NASA, among others, indicate that this level is no longer sufficient. The most recent observations and model calculations show that a reduction to 350 ppm CO<sub>2</sub> in the atmosphere may be necessary, or even that anthropologically emitted climate gases must be avoided entirely 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<sub>2</sub> 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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## 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.

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## 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,<sup>1</sup> 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

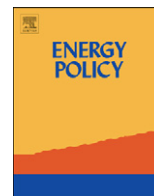
experimenting with new technologies as it is a relatively small country with 4.4 million people, it is an island which makes it specifically attractive for the implementation of alternative transport technologies such as electric vehicles, and it has an abundant resource of renewable energy in the form 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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<sup>1</sup> Ireland refers to the Republic of Ireland only unless otherwise specified.



# 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.

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## 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<sub>2</sub>) 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.

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## 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<sub>2</sub> 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.

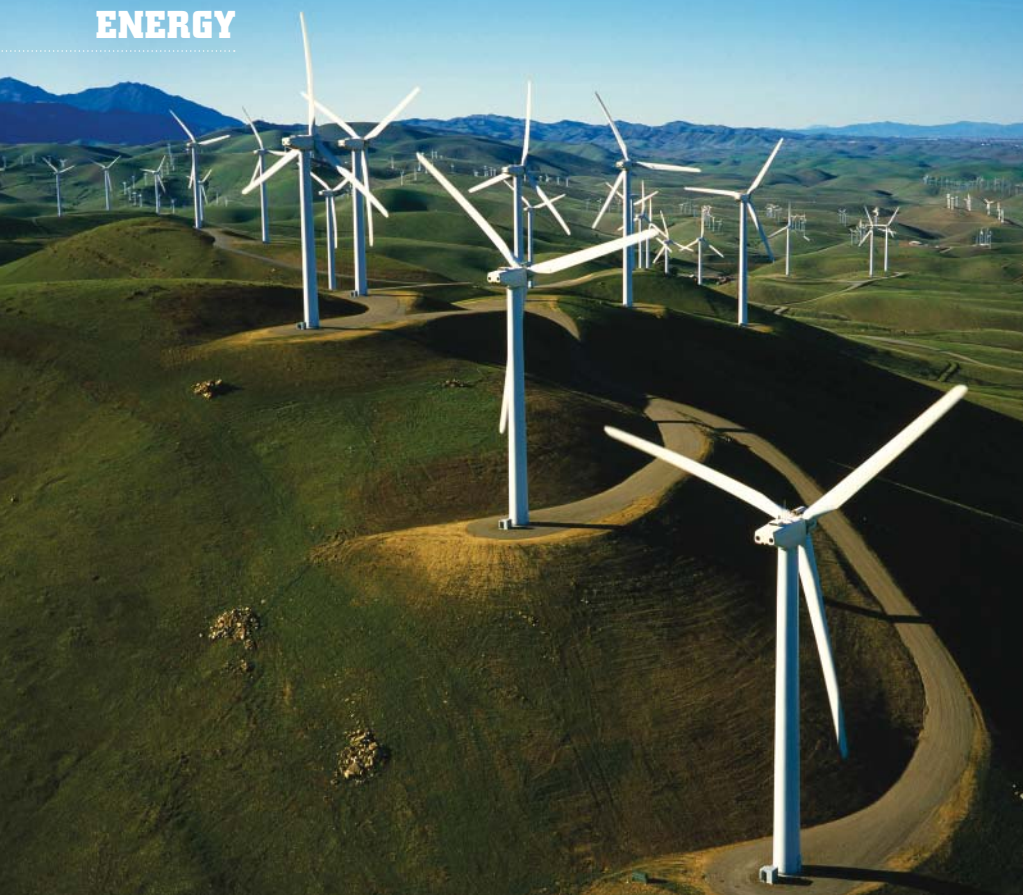
In Denmark, on the one hand, CO<sub>2</sub> emissions per capita have for many years been among the highest in the world on the other, an active energy policy has already led to remarkable results in the decrease of emissions [11]. For a period of 35 years, Denmark has managed to stabilise the primary 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<sub>2</sub> 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

# 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.

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**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.

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**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  $350 \text{ kg/m}^3$ , an average elevation change of  $1.8 \pm 0.3 \text{ cm/year}$  over an area of  $7.1 \text{ million km}^2$  for the East Antarctic interior (table S1) corresponds to a mass gain of  $45 \pm 7$  billion metric tons of water per year and a corresponding sea-level drop of  $0.12 \pm 0.02 \text{ mm/year}$ . 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  $1.8 \text{ cm/year}$  average  $dH/dt$  over the entire East Antarctic ice sheet ( $\sim 10 \text{ million km}^2$ ) would correspond to a sea-level drop of  $0.18 \text{ mm/year}$  (assuming a recent change and snow density of  $350 \text{ kg/m}^3$ ), nearly as large as the most recent estimate of  $0.20 \text{ mm/year}$  (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  $0.16 \text{ mm/year}$  (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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#### Supporting Online Material

[www.sciencemag.org/cgi/content/full/1110662/DC1](http://www.sciencemag.org/cgi/content/full/1110662/DC1)

Materials and Methods

Figs. S1 to S4

Table S1

References and Notes

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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