Supplementary material

Our review of 24 studies of 100% renewable electricity systems finds that none individually, nor the literature in aggregate, provides compelling evidence for even the basic feasibility (as defined in the main text) of such proposed systems. As shown in Supplementary Table 1, many of the assessed studies were scored as zero against our framework. This is all the more important given that our review gave no assessment whatsoever of important viability aspects such as financial cost, planning constraints, technology assumptions, governance and policy requirements and land use conflicts. The true costs of 100% renewable electricity systems cannot be determined on the basis of systems that are not even technically feasible, yet at this time that is all the literature offers.

As shown in Supplementary Table 1, few studies did system simulations on timeframes of < 1 hour. Only two studies specifically sought to address extreme but credible conditions of low availability of the renewable resources. Almost all studies assumed away the constraints of transmission requirements, with some (unrealistically) assuming copperplate networks, others applying simplistic cost multipliers to compensate, and none undertaking actual power-flow modelling. Only one author, Australian Energy Market Operator [1], seemed aware of the importance of maintaining ancillary services in the face of wide-scale modifications of existing, known and understood systems and practices.

In Supplementary Table 2, we exclude the transmission criteria, effectively granting all work the assumption of a copperplate network, and re-score all studies out of a total of six. This is to acknowledge that the use of transmission is well known and understood and may be argued to be more a matter of viability (chiefly cost, planning constraints and pace of roll-out)

One of our main findings has been the failure of studies examining 100% renewable electricity and energy to adhere to mainstream projections of demand for both energy and electricity. Put differently, many of the studies we examined created, as a starting point, a highly modified energy/electricity demand scenario that is either unlikely to materialise or, if it did, would likely have deleterious consequences for the advancement of human welfare in the developing world. As shown in Supplementary Fig.1, even the strongest mitigation scenario under consideration by the IPCC projects growth in primary energy demand to the end of the century. This calls into question the usefulness and validity of any subsequent outputs including simulations of hypothetical supply solutions meeting these contrived demand scenarios. It is apparent that demand scenarios need to be regionally specific and, for the proposed solutions to be considered robust, a reasonable range of projected demand outcomes must to be considered.

Many of the studies we considered in our review pertain to Australia. Demand for electricity in Australia is projected to continue to grow mainly on the back of a strongly increasing population [2]. While recent years have defied this trend with an anomalous reduction in total electricity demand, increased demand remains the mainstream forecasting expectation as shown in Supplementary Fig. 1 Primary energy (exajoules [EJ] year-1) and emissions of carbon dioxide (gigatonnes [Gt] year-1) under Intergovernmental Panel on Climate Change (IPCC) scenario RCP2.6. [46]. Sources: emissions values from RCP Database 2015 [47]; energy values from van Vuuren et al [46].

Supplementary Fig. 2. Here we see that the assumed demand for Elliston *et al*. [3], based on actual 2011 consumption values, is unlikely to be the demand across a timeframe where implementation of broad-scale energy transition can occur. So while this choice was defensible in that the simulation mimics both actual quantity of electricity demanded and the actual pattern of that demand, the quantity is likely to fall far short of needs over relevant timeframes. In the case of Wright & Hearps [4], we see from Supplementary Fig. 3 that primary energy was assumed to reduce by 58% in a little over 10 years, with a corresponding sharp increase in electrification, giving an electricity demand at the highest end of the range of mainstream projections; this outcome will certainly not occur. In contrast, the two scenarios applied by the Australian Energy Market Operator [1] are placed far enough into the future to be relevant and reasonable with regard to energy transitions, and encompass a range that is consistent with more recent trends and projections (**Error! Reference source not found.**). The outputs are thus worthy of closer consideration.

California presents a similar case, where projections from three sources point toward the likelihood that electricity consumption will continue to increase (Supplementary Fig. 3). The scenario applied by Hart and Jacobson [5] falls at the lower end of this range. However, Jacobson *et al*. [6] assumed the complete electrification of all energy use in California and applied a scenario where electricity consumption is 1375 TWh year^{-1}, 567% of the baseline year (2010) and 261% of the 2050 electricity demand under the *Efficiency, Clean Electricity Electrification* scenario of Wei *et al*. [7] This result is a stark outlier and suggests the assumptions of energy transition under Jacobson *et al*. [6] are unrealistic. All subsequent findings from that work must be discarded.

Other locations around the world, including Japan and much of Northern Europe, have base scenarios of steady or even falling energy demand. In the case of Denmark, base projections of primary energy are just +14% on 2004 values [8]. The scenario applied by Lund *et al*. [8] to test the potential of 100% renewable electricity applies a scenario of -59% primary energy compared to base expectations for 2050 [8]. This suggests a large change in the nature of energy consumption across the entire Danish economy, far beyond current expectations. Again, all subsequent outputs can be largely disregarded as unrealistic.

What might be the requirements for storage under a 100% renewable electricity system?

The literature addressing storage requirements under high-penetration renewable-electricity scenarios provides some insight into the scale of the potential requirements. One study purporting to identify the storage needs for a 100%-renewable system for Europe did so without estimating actual capacity requirements or costs; it also assumed unconstrained transmission [9]. Another Europe-focussed study cautioned that the "technical feasibility" of the required storage is questionable, highlighting the land constraints for pumped-hydro storage and the nascent stage of development of batteries at the terawatt hour (TWh) scale, along with large-scale production of hydrogen or methane. A study of the Electric Reliability Council of Texas (ERCOT) network (which provides 90% of the load of Texas for about 24 million customers) [10] suggests that a scenario of just 80% variable renewable generation requires a full day of storage capacity to ensure reliable supply. At 34 GW of delivered power, that requirement for Texas is 160% of the current installed electricity storage in the entire United States [11]. Additional storage capacity had diminishing return in terms of the percentage of supply that can be provided by variable renewable energy [11]. An attempt to identify global energy storage needs under 100% renewable energy suggests over 11,000 TWh of electricity would need to be provided by storage, which is 35% of global electricity demand (based on 2010 demand) [12]. That figure alone is ten times the theoretical maximum generation from all grid-connected storage in the world today, of which > 99% is pumped hydro [13], and the study did not identify the actual installed capacity requirements. The storage requirements for Japan under a 100% renewable-energy system is estimated to be 41 TWh [14]. For context, an electric car fleet of 35 million vehicles would provide < 5% of that capacity, and would be clearly ill-suited to cover the long-term supply fluctuations needed to ensure reliability [14].

Case study for policy makers: high-penetration renewables in South Africa

In August 2016, the Council for Scientific and Industrial Research (CSIR) Energy Centre of South Africa released a report outlining high-penetration renewable scenarios for South Africa [15]. The report proposed a system that provides 86% of the total electricity demand from renewable sources. This percentage (being < 95%) rendered the report outside the screening criteria outlined in the main text. However, many of the issues remain relevant and an appraisal of this report demonstrates the utility of our proposed framework for policy-makers.

Publicity accompanying the release included the following statements regarding feasibility:

Instead of renewable energy playing only a modest and supportive role in the future supply mix, research conducted by the Council for Scientific and Industrial Research (CSIR) Energy Centre shows that, having the bulk of the country's generation arising from wind and solar is not only technically feasible, but also the lowest-cost option … The outcome shows that it is technically feasible for such a 30 GW mix to supply the 8 GW baseload in as reliable a manner as conventional baseload generators, *while the economic analysis suggests that such a mix will deliver electricity at a blended cost of 100c/kWh* [16].

South Africa is a developing nation of over 50 million people with a high reliance on coal for existing electricity generation [15]. The decisions made by policy makers in nations like South Africa will have a material impact on the trajectory of global greenhouse gas emissions in this century. The framework we proposed in the main text provides a quick and reliable means of testing the assertion of feasibility, thus equipping policy-makers to scrutinise such claims. In Supplementary Table 4 we have scored this report against our framework. We discuss each score with reference to the study.

Criterion I: Demand

The CSIR study assumes for its high-penetration scenario an annual demand of 261 TWh year^{-1}. This figure is 15% greater than the current volume of electricity distributed in South Africa (227 TWh) [17]. That figure is similar to annual electricity demand in Australia today, a nation with less than half the population of South Africa (24 million people). The population of South Africa (currently approximately 54 million people) is expected to reach 67.3 million people by 2035 [18]. The Integrated Resource Plan from the South African Department of Energy suggests annual electricity demand in South Africa in 2030 will be 436 TWh, 70% higher than current demand [15]. Load-shedding is currently a regular occurrence in South Africa due to lack of supply [19]. Currently, consumption is constrained by supply and thus the true electricity demand is not known [19]. The Institute of Security Studies advises in the context of South Africa that energy planners need to err on the side of optimism in growth forecasts [19]. The CSIR study has taken the opposite approach.

We argue that a policy maker could have little doubt that the electricity demand proposed by the high-penetration renewable scenario from CSIR is not realistic and not in keeping with the imperative of alleviating wide-spread poverty in South Africa. Based on these findings, we gave a zero score for this criterion. This unrealistic assumption has an obvious and material impact on the cost inferred by CSIR for a reliable system. We discuss this below under Criterion 2.

Criterion II: Reliability

The CSIR simulated over three years of demand, using meteorological data from across South Africa to assess renewable-resource availability to 15-minute intervals. This is finer resolution than many of the studies we examined in the main text. With the additional dispatchable back-up, this study asserts that the proposed supply reliably meets the demand. The report explicitly identifies the lowest supply period of wind and solar in that three-year simulation [15]. However, there is no evidence that the simulation identified a credible extreme event over, for example, a 100-year timeframe. Hence, we have the study a score of 2.5 for simulating to 15-minute intervals.

Note however that the assumed demand scenario interacts with the supply reliability in a material way. Page 43 of the report identifies the highest residual load, at the time of lowest wind and solar supply, of 34 GW [15]. However, this is for a scenario where electricity demand is nearly unchanged from today. In a more realistic scenario where electricity demand has increased 70% from today, the residual load would be far greater. For while more wind and solar could be added to serve the larger demand in average conditions, the correlated supply indicated in Bischof-Niemz and Mushwana [15] means this additional capacity would be of little additional benefit during the periods of extremely low supply. The residual load could well be double the suggested 34 GW. This would add cost in the form of a greater low-utilisation back up. As identified in the report (page 8), changes to the assumed full-load hours for conventional generators changes the fixed-cost components per kWh [15]. This additional, low-utilisation, conventional back-up could materially impact the average price of electricity across the modelled period.

Criterion III: Transmission

The CSIR study has made the assumption of a copperplate network. There was no power-flow modelling. The report indicates that the geographic distribution of supply assumed from wind and solar covers all of South Africa. Similarly, the study maps all of South Africa for solar potential, and refers only to “exclusion zones”. Based on work done for Europe, it might be that reaping most of the benefits of this distribution would require a transmission network perhaps five to six times greater than that required under a centralised supply model [20]. The required network for this system to function has not been identified and hence the costs proposed for the system are incomplete.

Criterion IV: Ancillary services

The study offers no solutions in relation to ancillary services. The report declares additional analyses are required to determine stable operations of power-electronics based power systems [15]. This acknowledges that the proposed system will at times need to operate with a virtual absence of synchronous generation. As discussed in the main text, the novel solutions to this challenge are nascent, with some investigation under way, no demonstration or comprehensive modelling at relevant scale and few demonstrations globally [21]. Proposed solutions such as the widespread use of large-capacity batteries to provide frequency control will add cost to the proposed system. An actual portfolio of solutions has not been described. Hence, the costs proposed for the system are incomplete and the claim of feasibility is dubious.

Summary

The CSIR study has improved our understanding of what might be provided by wind and solar photovoltaics in South Africa in the future. There can be no argument that the falling levelized cost of electricity from these sources boosts the prospects for their economic deployment. Overall we conclude both the use of the terms “technically feasible” and the attempted costing of the proposed system are inappropriate and premature, being undermined by (*i*) an unrealistic electricity-demand scenario, (*ii*) no simulation to finer time scales, (*iii*) no consideration of extreme events beyond three years of data, (*iv*) no identified transmission requirements, and (*iv*) no solutions to provide vital ancillary services. Our framework thus provides policy-makers with a simply and readily applied screen the actual feasibility of proposed electricity solutions, including other recently published studies [22, 23]

Supplementary Table 1 Scoring against feasibility criteria for 25 100% renewable electricity scenarios. Individual criterion are defined in the Methods of the main text. 'Coverage' refers to the spatial/geographic area of each scenario. 'Total' means the aggregated score for the scenario across all criteria with a maximum possible score of 7. 'Scenario' refers to the scenario that we selected from the study under examination for assessment against these criteria, where there were several named scenarios. 'Scenario Year(s)' refers to the year(s) in which the scenario purports to provide a 100% renewable electricity for the Coverage area. Where the Scenario Year(s) are historic, the authors have replicated previous years.

				Criteria							
Study	Coverage	Scenario name	Scenario Year(s)	Realistic demand	Reliability simulation: Hourly	Reliability simulation: Half-hourly	Reliability simulation: Five minute	Extreme event check	Transmission requirements	Ancillary services	Total
Mason *et al.* [24, 25]	**New Zealand**	**GM3**	2020	1	1	1	0	1	1	0	**4**
Australian Energy Market Operator (1) [1]	**Australia (NEM*- only)**	**Scenario 1 2050**	2050	1	1	0	0	0	1	0.5	**3.5**
Australian Energy Market Operator (2) [1]	**Australia (NEM*–only)**	**Scenario 2 2050**	2050	1	1	0	0	0	1	0.5	**3.5**
Jacobson *et al.* [26]	**Contiguous USA**	**N/A**	2050-2055	0	1	1	1	0	0	0	**3**
Wright & Hearps [4]	**Australia (total)**	**Plan**	2050	0	1	1	0	0	1	0	**3**
Fthenakis *et al.* [27]	**USA**	**2050**	2050	1	0	0	0	1	0	0	**2**
Connolly *et al.* [28]	**Ireland**	**COMBO**	2005-2007 & 2005-2010	1	1	0	0	0	0	0	**2**
Fernandes & Ferreira [29]	**Portugal**	**Scenario 3**	2007	1	1	0	0	0	0	0	**2**
Krajacic *et al.* [30]	**Portugal**	**100% RES**	2050	1	1	0	0	0	0	0	**2**
Hart & Jacobson [5]	**California ISO†**	**N/A**	2010	1	1	0	0	0	0	0	**2**
Esteban *et al.* [14]	**Japan**	**Low-cost**	2010	1	1	0	0	0	0	0	**2**
Allen et al. [31]	**Britain**	**ZCB**	2050	0	2	0	0	0	0	0	**2**
Elliston, MacGill & Diesendorf [32]	**Australia (NEM*-only)**	**Low cost, 5% discount rate**	2050	0	1	0	0	0	0	0.5	**1.5**
Budischak *et al.* [33]	**PJM‡ Interconnection**	**Least-cost optimised 99.9% renewable supply**	1999-2002	0	1	0	0	0	0	0	**1**
Lund & Mathiesen [8]	**Denmark**	**IDA 2050 Combination**	2030	0	1	0	0	0	0	0	**1**

Elliston, Diesendorf & MacGill [3]	**Australia (NEM-only)**	**NEM simulation**	2050	0	1	0	0	0	0	0	**1**
Jacobsen *et al.* [35]	**New York State**	**N/A**	2006	1	0	0	0	0	0	0	**1**
Price Waterhouse Coopers [36]	**Europe and North Africa**	**2050 low-carbon**	2050	1	0	0	0	0	0	0	**1**
European Renewable Energy Council [37]	**European Union 27**	**N/A**	2100	1	0	0	0	0	0	0	**1**
ClimateWorks [38]	**Australia**	**N/A**	2060	1	0	0	0	0	0	0	**1**
World Wildlife Fund [39]	**Global**	**N/A**	2100	0	0	0	0	0	0	0	**0**
Jacobsen & Delucchi [40, 41]	**Global**	**WWS**	2050	0	0	0	0	0	0	0	**0**
Jacobson *et al.* [6]	**California**	**WWS**	2050	0	0	0	0	0	0	0	**0**
Greenpeace (Teske *et al.*) [42]	**Global**	**100% renewables grid**	2050	0	0	0	0	0	0	0	**0**

Supplementary Table 2 Revised scoring against feasibility criteria for 25 100% renewable electricity scenarios. Individual criterion are defined in the Methods of the main text. 'Coverage' refers to the spatial/geographic area of each scenario. 'Total' means the aggregated score for the scenario across all criteria with a maximum possible score of 6. 'Scenario' refers to the scenario that we selected from the study under examination for assessment against these criteria, where there were several named scenarios. 'Scenario Year(s)' refers to the year(s) in which the scenario purports to provide a 100% renewable electricity for the Coverage area. Where the Scenario Year(s) are historic, the authors have replicated previous years. Scoring for *Transmission requirements* has been excluded, indicated by *NA*.

				Criteria							
Study	Coverage	Scenario name	Scenario Year(s)	Realistic demand	Reliability simulation: Hourly	Reliability simulation: Half-hourly	Reliability simulation: Five minute	Extreme event check	Transmission requirements	Ancillary services	Total
Mason *et al.* [24, 25]	**New Zealand**	**GM3**	2020	1	1	1	0	1	NA	0	**3**
Australian Energy Market Operator (1) [1]	**Australia (NEM[§]- only)**	**Scenario 1 2050**	2050	1	1	0	0	0	NA	0.5	**2.5**
Australian Energy Market Operator (2) [1]	**Australia (NEM[*]–only)**	**Scenario 2 2050**	2050	1	1	0	0	0	NA	0.5	**2.5**
Jacobson *et al.* [26]	**Contiguous USA**	**N/A**	2050-2055	0	1	1	1	0	NA	0	**3**
Wright & Hearps [4]	**Australia (total)**	**Plan**	2050	0	1	1	0	0	NA	0	**2**
Fthenakis *et al.* [27]	**USA**	**2050**	2050	1	0	0	0	1	NA	0	**2**
Connolly *et al.* [28]	**Ireland**	**COMBO**	2005-2007 & 2005-2010	1	1	0	0	0	NA	0	**2**
Fernandes & Ferreira [29]	**Portugal**	**Scenario 3**	2007	1	1	0	0	0	NA	0	**2**
Krajacic *et al.* [30]	**Portugal**	**100% RES**	2050	1	1	0	0	0	NA	0	**2**
Hart & Jacobson [5]	**California ISO[**]**	**N/A**	2010	1	1	0	0	0	NA	0	**2**
Esteban *et al.* [14]	**Japan**	**Low-cost**	2010	1	1	0	0	0	NA	0	**2**
Allen et al. [31]	**Britain**	**ZCB**	2050	0	2	0	0	0	NA	0	**2**
Elliston, MacGill & Diesendorf [32]	**Australia (NEM[*]-only)**	**Low cost, 5% discount rate**	2050	0	1	0	0	0	NA	0.5	**1.5**
Budischak *et al.* [33]	**PJM[††] Interconnection**	**Least-cost optimised 99.9% renewable supply**	1999-2002	0	1	0	0	0	NA	0	**1**
Lund & Mathiesen [8]	**Denmark**	**IDA 2050 Combination**	2030	0	1	0	0	0	NA	0	**1**
Cosic, Krajacic & Duic [34]	**Macedonia**	**100% RES 2050**	2020	0	1	0	0	0	NA	0	**1**

[§] National Electricity Market, covering Queensland, New South Wales, Victoria, South Australia and Tasmania, making up approximately 85% of total Australian electricity demand
[**] Independent Service Operator
[††] Pennsylvania New Jersey Maryland

Elliston, Diesendorf & MacGill [3]	**Australia (NEM-only)**	**NEM simulation**	2050	0	1	0	0	0	NA	0	**1**
Jacobsen *et al.* [35]	**New York State**	**N/A**	2006	1	0	0	0	0	NA	0	**1**
Price Waterhouse Coopers [36]	**Europe and North Africa**	**2050 low-carbon**	2050	1	0	0	0	0	NA	0	**1**
European Renewable Energy Council [37]	**European Union 27**	**N/A**	2100	1	0	0	0	0	NA	0	**1**
ClimateWorks [38]	**Australia**	**N/A**	2060	1	0	0	0	0	NA	0	**1**
World Wildlife Fund [39]	**Global**	**N/A**	2100	0	0	0	0	0	NA	0	**0**
Jacobsen & Delucchi [40, 41]	**Global**	**WWS**	2050	0	0	0	0	0	NA	0	**0**
Jacobson *et al.* [6]	**California**	**WWS**	2050	0	0	0	0	0	NA	0	**0**
Greenpeace (Teske *et al.*) [42]	**Global**	**100% renewables grid**	2050	0	0	0	0	0	NA	0	**0**

Supplementary Table 3 Summary of assumed energy storage for 25 100% renewables studies.

Study	Coverage	Storage reliant (Y/N)	Details
Mason *et al*. [24, 25]	**New Zealand**	Y	Relies on stored hydro energy and use of pumped lake storage to historic values with unconstrained ramping or flow
Australian Energy Market Operator (1) [1]	**Australia (NEM–only)**	Y	CST with molten salt, biogas stored in the existing gas systems, biomass and additional pumped hydro
Australian Energy Market Operator (2) [1]	**Australia (NEM–only)**	Y	CST with molten salt, biogas stored in the existing gas systems, biomass and additional pumped hydr006F
Jacobson *et al. [26]*	**Contiguous USA**	Y	Assumes use of solar thermal with molten salt storage (16 hr for baseload plants, 6 hr for peak plants) at approximately 1500 GW installed by 2050 (up from 9 GW currently). Assumes use of compressed air energy storage in geological formations with working capacity of plants in 2050 a factor of 10 greater than the current working underground gas storage capacity in the US.
Wright & Hearps [4]	**Australia (total)**	Y	Assumes 60% of annual electricity provided by 42.5 GW installed of concentrating solar thermal plant with 17 hours of energy storage
Fthenakis *et al*. [27]	**USA**	Y	Assumes use of solar thermal with molten salt storage (16 hr for baseload plants, 6 hr for peak plants) at approximately 1500 GW installed by 2050 (up from 9 GW currently). Assumes use of compressed air energy storage in geological formations with working capacity of plants in 2050 a factor of 10 greater than the current working underground gas storage capacity in the US.
Allen *et al*. [31]	**Britain**	Y	180 TWh of surplus electricity is used to produce hydrogen (126 TWh), which could be stored in salt caverns. It is used to produce syn gas (27 TWh per year) that is then used to provide back-up electricity (14 TWh) via 45 GW of gas power stations
Connolly *et al*. [28]	**Ireland**	N	
Fernandes & Ferreira [29]	**Portugal**	Y	Hydro dam storage increases from 2117 to 6971 MW
Krajacic *et al*. [30]	**Portugal**	Y	6848 GWh storage assumed across hydro reservoirs, hydrogen storage and batteries
Esteban *et al*. [14]	**Japan**	Y	
Budischak *et al*. [33]	**PJM Interconnection**	Y	Unspecified; however, indicates strong dependence on concentrating solar power with 3-hr storage, and assumes additional load balancing will be available from the following: CSP with storage longer than 3 h, additional pumped hydroelectric storage, distributed or large-scale battery storage, compressed-air storage, flywheels, seasonal heat storage in soil, out-of-state WWS resources, the addition of flexible loads such as electric vehicles , vehicle-to-grid methods
Elliston, MacGill & Diesendorf [43]	**Australia (NEM–only)**	Y	Assumes 15.6 GW installed of solar thermal generation with 15 hours of storage.
Lund & Mathiesen [8]	**Denmark**	N	No indication of direct storage reliance in meeting electricity demand. Excess electricity is assumed converted to hydrogen for substitution of fossil fuels in other areas of energy demand

Cosic, Krajacic & Duic [34]	**Macedonia**	Y	Increase pumped hydro storage from 350 to 1500-1800 MW
Elliston, Diesendorf & MacGill [3]	**Australia (NEM–only)**	Y	Assumes approximately 13% of electricity generated by concentrating solar thermal with storage
Jacobsen *et al.* [44]	**New York State**	Y	Details are not disclosed. The study states that it requires: storing energy in thermal storage media, batteries or other storage media at the site of generation or use; and storing energy in electric-vehicle batteries for later extraction. Further, indicates the application of using concentrated solar power storage to provide solar power at night; and storing excess energy at the site of generation with pumped hydroelectric power, compressed air (e.g., in underground caverns or turbine nacelles), flywheels, battery storage packs, or batteries in electric vehicles.
Price Waterhouse Coopers [36]	**Europe and North Africa**	Y	No quantification of storage requirements. Repeated reference to the role of concentrating solar thermal with storage, pumped hydro storage and other, undefined "storage".
European Renewable Energy Council [45]	**European Union 27**	Y	Indicates approximately 25+ times expansion in solar thermal with storage, references decentralised storage devices with solar PV
ClimateWorks [38]	**Australia**	Y	Solar thermal with 6 hr storage is deployed for ~ 20% of generated electricity; however, no detail is provided regarding installed capacity. The underlying ESM model also allows battery storage in the grid
World Wildlife Fund [39]	**Global**	Y	Depends on expansion of pumped hydro, centralised hydrogen generation and storage, and heat storage
Jacobsen & Delucchi [40, 41]	**Global**	Y	Assumes storage with batteries, hydrogen gas, pumped hydro-electric power, compressed air, flywheels, thermal storage medium, electric vehicles with smart charging.
Jacobson *et al*. [6]	**California**	Y	Assumes utility concentrating solar power with storage
Greenpeace (Teske *et al*.) [42]	**Global**	Y	22% of electricity generated from solar thermal with storage systems. Hydrogen storage in use. General remark on dependence on "expansion of smart grids, demand side management and storage capacity".

Supplementary Table 4 Scoring against feasibility criteria for a single, high-penetration renewable energy scenario. 'Coverage' refers to the spatial/geographic area of each scenario. 'Total' means the aggregated score for the scenario across all criteria with a maximum possible score of 7. Criteria are defined in Methods. For concision, the 'Reliability' column aggregates all four potential scores for reliability into a single score.

		Criterion				
Study	**Coverage**	**I (Demand)**	**II (Reliability)**	**III (Transmission)**	**IV (Ancillary)**	**Total**
CSIR [15]	**South Africa**	0	2.5	0	0	2.5

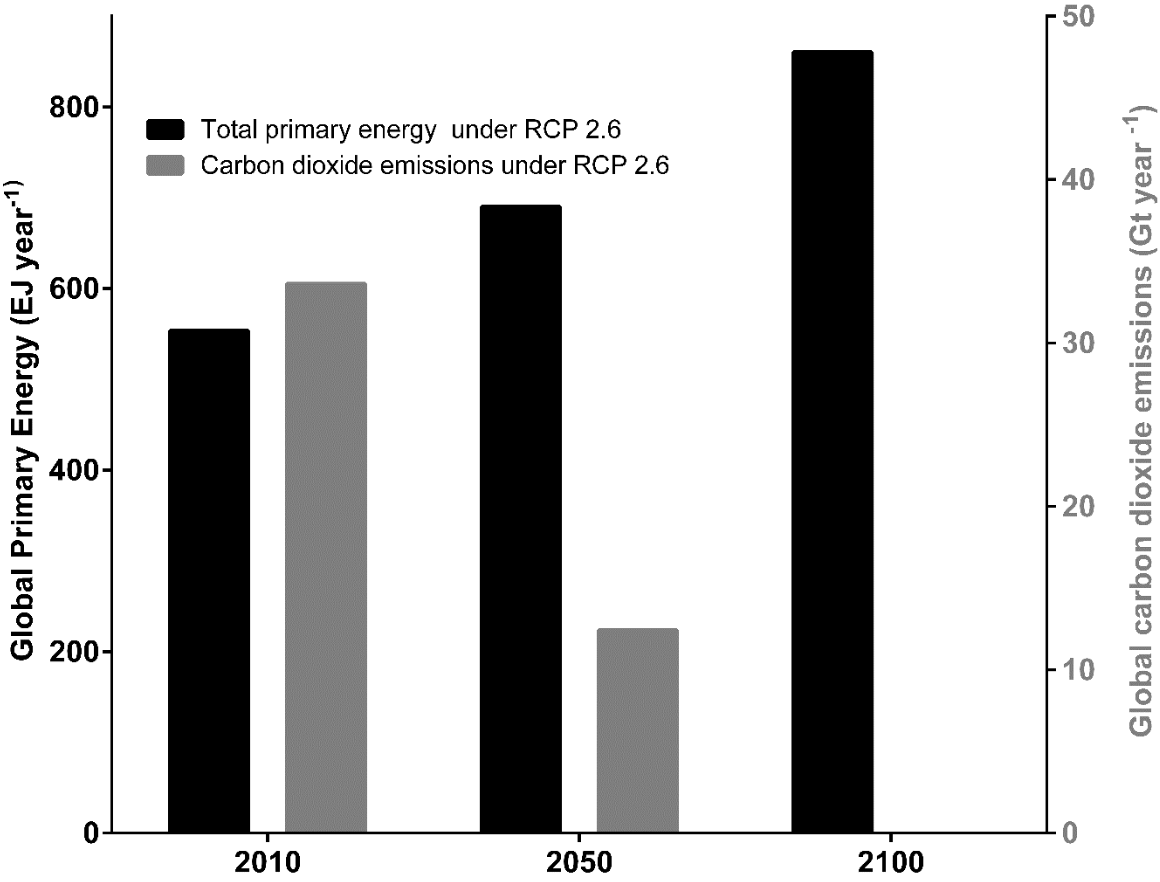
Supplementary figure captions

Supplementary Fig. 1 Primary energy (exajoules [EJ] year-1) and emissions of carbon dioxide (gigatonnes [Gt] year-1) under Intergovernmental Panel on Climate Change (IPCC) scenario RCP2.6. [46]. Sources: emissions values from RCP Database 2015 [47]; energy values from van Vuuren et al [46].

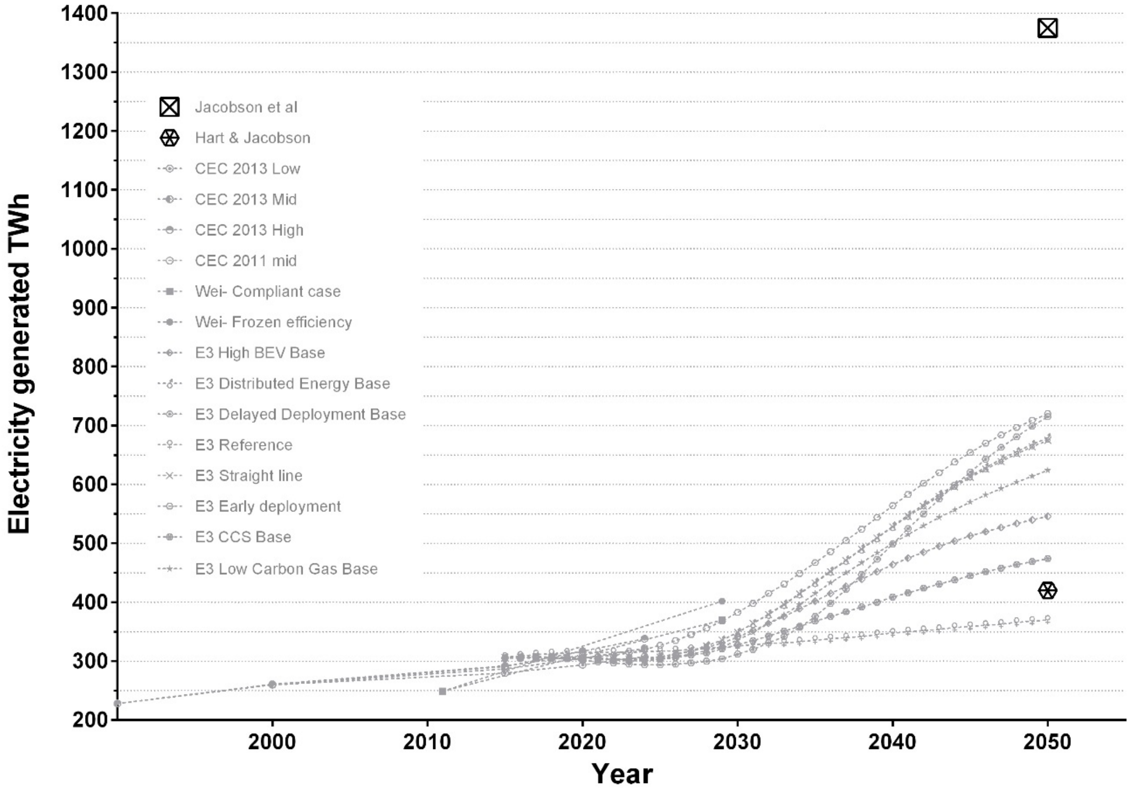
Supplementary Fig. 2 Comparison of scenarios for Australian electricity consumption (terawatt-hours, TWh) from Bureau of Resources and Energy Economics (BREE), ACIL Allen, Australian Energy Market Operator/Independent Market Operator (AEMO/IMO), Australian Government Treasury Strong Growth, Low Pollution (SGLP) [all sourced from 48], National Electricity Forecasting Report (NEFR) [49], Department of Industry and Science (DOIS) [50], Wright and Hearps [4] and Elliston *et al.* [3] (EDM), Australian Energy Market Operator 100% Renewables [1] (AEMO). Figures from National Electricity Forecasting Report were converted from National Electricity Market figures to Australia-wide figures by multiplying annual data by 1.14

Supplementary Fig. 3 Comparison of projected Californian electricity demand (terawatt-hours, TWh) between scenarios from E3 [51], Kavalec and Sullivan [52] (CEC) , Wei *et al.* [7] (Wei), Jacobson *et al.* [6] and Hart and Jacobson [5],

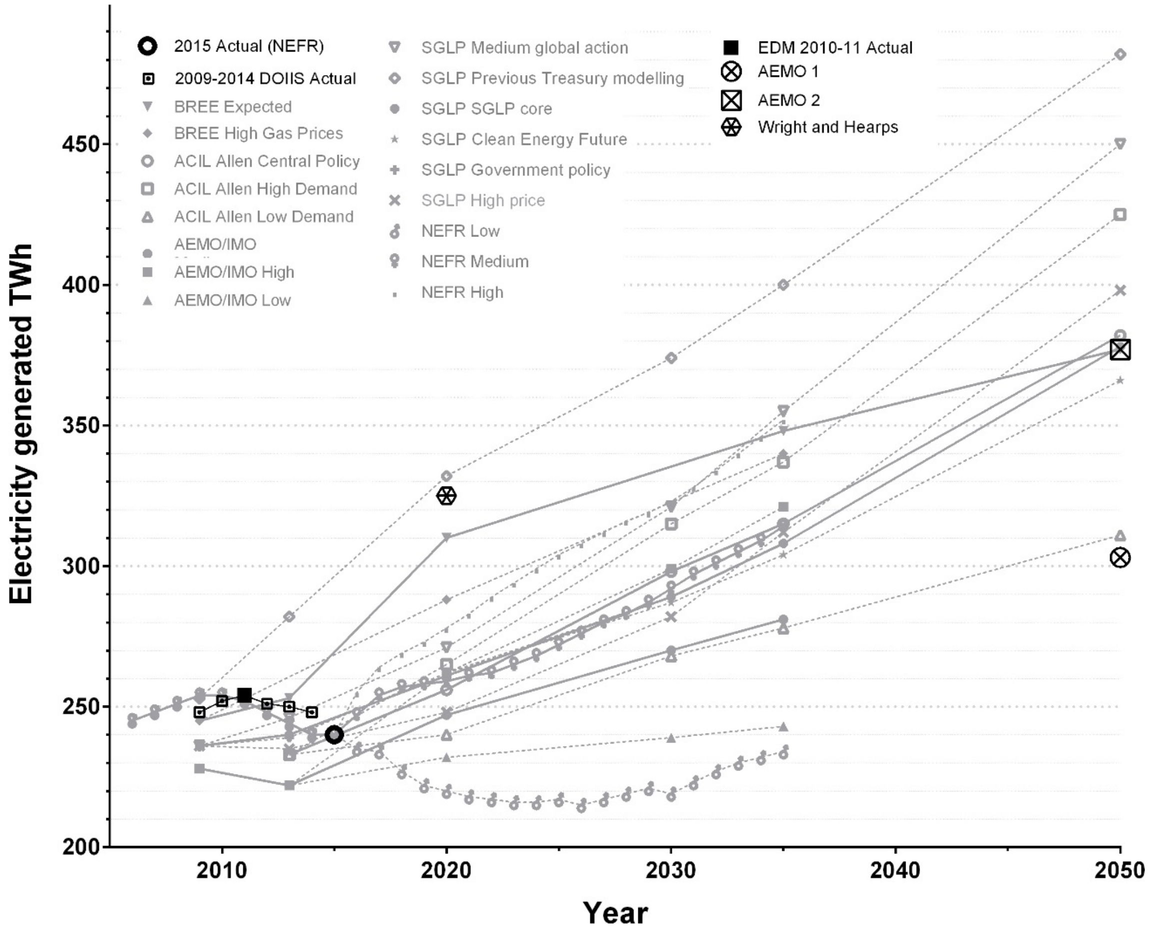
Supplementary Fig. 1



Supplementary Fig. 2



Supplementary Fig. 3



Notes and references

[1] Australian Energy Market Operator Ltd. 100 per cent renewables study- modelling outcomes. New South Wales2013.
[2] Bradshaw C, Brook BW. Human population reduction is not a quick fix for environmental problems. Proceedings of the National Academy of Science. 2014;111:16610-5.
[3] Elliston B, Diesendorf M, MacGill I. Simulations of scenarios with 100% renewable electricity in the Australian National Electricity Market. Energy Policy. 2012;45:606-13.
[4] Wright, Hearps P. Zero Carbon Australia Stationary Energy Plan. Melbourne, Victoria2010.
[5] Hart EK, Jacobson MZ. The carbon abatement potential of high penetration intermittent renewables. Energy & Environmental Science. 2012;5:6592.
[6] Jacobson MZ, Delucchi MA, Ingraffea AR, Howarth RW, Bazouin G, Bridgeland B, et al. A roadmap for repowering California for all purposes with wind, water, and sunlight. Energy. 2014;73:875-89.
[7] Wei M, Nelson JH, Greenblatt JB, Mileva A, Johnston J, Ting M, et al. Deep carbon reductions in California require electrification and integration across economic sectors. Environmental Research Letters. 2013;8:014038.
[8] Lund H, Mathiesen BV. Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. Energy. 2009;34:524-31.
[9] Rasmussen MG, Andresen GB, Greiner M. Storage and balancing synergies in a fully or highly renewable pan-European power system. Energy Policy. 2012;51:642-51.
[10] Electric Reliability Council of Texas Inc. About ERCOT. 2016.
[11] Denholm P, Hand M. Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. Energy Policy. 2011;39:1817-30.
[12] Pleßmann G, Erdmann M, Hlusiak M, Breyer C. Global Energy Storage Demand for a 100% Renewable Electricity Supply. Energy Procedia. 2014;46:22-31.
[13] International Energy Agency. Technology Roadmap Energy Storage. Paris, France2014.
[14] Esteban M, Zhang Q, Utama A. Estimation of the energy storage requirement of a future 100% renewable energy system in Japan. Energy Policy. 2012;47:22-31.
[15] Bischof-Niemz T, Mushwana C. High-renewables scenarios: Thought experiments for the South African power system. Pretoria, South Africa2016.
[16] Creamer T. Wind, solar can supply bulk of South Africa's power at least cost, CSIR model shows. Johannnesburg, South Africa: Creamer Media; 2016.
[17] Statistics South Africa. Electricity generated and available for distribution (Preliminary) - December 2016. Pretoria, South Africa2016.
[18] Cilliers J. South African Futures 2035: Can Bafana Bafana still score? Pretoria, South Africa2015.
[19] Hedden S. Gridlocked: A long-term look at South Africa's Electricity Sector. Pretoria, South Africa2015.
[20] Rodríguez RA, Becker S, Andresen GB, Heide D, Greiner M. Transmission needs across a fully renewable European power system. Renewable Energy. 2014;63:467-76.
[21] Christiensen C, Murry B. Energy Storage Study. Sydney, NSW2015.
[22] Sáfián F. Modelling the Hungarian energy system – The first step towards sustainable energy planning. Energy. 2014;69:58-66.
[23] Connolly D, Lund H, Mathiesen BV. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renewable and Sustainable Energy Reviews. 2016;60:1634-53.
[24] Mason IG, Page SC, Williamson AG. Security of supply, energy spillage control and peaking options within a 100% renewable electricity system for New Zealand. Energy Policy. 2013;60:324-33.
[25] Mason IG, Page SC, Williamson AG. A 100% renewable electricity generation system for New Zealand utilising hydro, wind, geothermal and biomass resources. Energy Policy. 2010;38:3973-84.
[26] Jacobson MZ, Delucchi MA, Cameron MA, Frew BA. Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. PNAS. 2015;112:1560-5.
[27] Fthenakis V, Mason JE, Zweibel K. The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US. Energy Policy. 2009;37:387-99.
[28] Connolly D, Lund H, Mathiesen BV, Leahy M. The first step towards a 100% renewable energy-system for Ireland. Applied Energy. 2011;88:502-7.
[29] Fernandes L, Ferreira P. Renewable energy scenarios in the Portuguese electricity system. Energy. 2014;69:51-7.
[30] Krajačić G, Duić N, Carvalho MdG. How to achieve a 100% RES electricity supply for Portugal? Applied Energy. 2011;88:508-17.
[31] Allen P, Blake L, Harper P, Hooker-Stroud A, James P, Kellner T. Zero Carbon Britain" Rethinking the Future. Powys, UK: Centre for Alternative Technology; 2013.
[32] Elliston B, MacGill I, Diesendorf M. Least cost 100% renewable electricity scenarios in the Australian National Electricity Market. Energy Policy. 2013;59:270-82.

[33] Budischak C, Sewell D, Thomson H, Mach L, Veron DE, Kempton W. Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time. Journal of Power Sources. 2013;225:60-74.
[34] Ćosić B, Krajačić G, Duić N. A 100% renewable energy system in the year 2050: The case of Macedonia. Energy. 2012;48:80-7.
[35] Jacobson MZ, Howarth RW, Delucchi MA, Scobie SR, Barth JM, Dvorak MJ, et al. Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight. Energy Policy. 2013;57:585-601.
[36] Price Waterhouse Coopers. 100% renewable electricity: A roadmap for Europe and North Africa. United Kingdom2010.
[37] Council ERE. RE-thinking 2050: A 100% Renewable Energy Vision for the European Union. Brussels, Belgium2010.
[38] ClimateWorks Australia, ANU, CSIRO, CoPS 2014. Pathways to Deep Decarbonisation in 2050: How Australia can prosper in a low carbon world: Technical report. Melbourne, Victoria: ClimateWorks Australia; 2014.
[39] Jeffries B, Deng Y, Cornelissen S, Klaus S. The energy report: 100% renewable energy by 2050. Gland, Switzerland: WWF International; 2011.
[40] Delucchi MA, Jacobson MZ. Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies. Energy Policy. 2011;39:1170-90.
[41] Jacobson MZ, Delucchi MA. Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Policy. 2011;39:1154-69.
[42] Teske S, Pregger T, Simon S, Naegler T, O'Sullivan M. energy [r]evolution. World Energy Scenario. 4th ed. Amsterdam, Netherlands: Greenpeace, Global Wind Energy Council & European Renewable Energy Council; 2012.
[43] Elliston B, MacGill I, Diesendorf M. Comparing least cost scenarios for 100% renewable electricity with low emission fossil fuel scenarios in the Australian National Electricity Market. Renewable Energy. 2014;66:196-204.
[44] Gilbraith N, Jaramillo P, Tong F, Faria F. Comments on Jacobson et al.'s proposal for a wind, water, and solar energy future for New York State. Energy Policy. 2013;60:68-9.
[45] European Renewable Energy Council. Re-thinking 2050: A 100% Renewable Energy Vision for the European Union. Brussels, Belgium2010.
[46] van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, et al. The representative concentration pathways: an overview. Climatic Change. 2011;109:5-31.
[47] van Vuuren DP, Eickhout B, Lucas PL, Elzen MGJd. Long-term multi-gas scenarios to stabilise radiative forcing - Exploring costs and benefits within an integrated assessment framework. Multigas Mitigation and Climate Policy. The Energy Journal. 2006.
[48] Brinsmead T.S., Hayward J, Graham P. Australian Electricity Market Analysis report to 2020 and 2030. Melbourne, Australia2014.
[49] Australian Energy Market Operator. National Electricity Forecasting Report. Sydney, NSW2015.
[50] Department of Industry and Science. 2015 Australian energy update. Canberra, ACT2015.
[51] Energy+Environmental Econonics. California Pathways Scenerios Data. San Francisco, California, USA: E3; 2015.
[52] Kavalec C, Nicholas Fugate, Bryan Alcorn, Mark Ciminelli, Asish Gautam, Kate, Sullivan MWG. California Energy Demand 2014-2024 Final Forecast, Volume 1: Statewide Electricity Demand, End-User Natural Gas Demand, and Energy Efficiency. California, USA2014.