Building renewable electricity systems: opportunities and challenges

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28 March 2023







Setting the stage: Climate-neutral electricity

The problem of dealing with variability, and possible solutions

Combinations that work, and how to make informed decisions





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The pivotal role of electricity



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Two simple steps to eliminate energy emissions



Emissions data: Climate Watch (2023), https://www.climatewatchdata.org/ghg-emissions?breakBy=sector&end_year=2019&start_year=1990





Why electrification? The triumph of solar and wind power



Globally massive resource of solar and wind power



Cho (2010). Science



Rapidly falling costs of solar and wind power



https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA Power Generation Costs 2020.pdf



The Economist

By Invitation



Dan Williama

Michael Liebreich: It takes time to scale new techs. We have no choice but to deploy the techs we have today. Of course, R&D in next-gen techs should continue at the same time.

https://www.economist.com/by-invitation/2023/02/07/michael-liebreich-wants-existing-low-carbon-technologies-to-be-scaled-up-much-faster https://www.economist.com/by-invitation/2022/11/08/vinod-khosla-says-rushing-to-meet-carbon-reduction-targets-by-2030-may-hinder-what-can-be-achieved-by-2050



Dan William

Vinod Khosla: Hoping to deploy today's techs globally is unrealistic. Wind and solar are not reliable enough; we need things like next-gen nuclear fission and fusion.



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LCOE: Levelised cost of electricity (or energy)

Depreciati

overnight investment cost (\$) * depreciation rate

LCOE = <u>annualised investment cost (\$)</u> average annual generation (kWh) + operational cost (\$/kWh)

Example: rooftop PV system with 1 kW capacity



Discount rate: 0.05 Lifetime: 20 years Investment cost: 375 \$/kW Size: 1 kW Annual generation: 1000 kWh

on rate
$$d = \frac{i(1+i)^n}{(1+i)^n - 1}$$

n: lifetime in years *i*: discount rate

 $i=0.05, n=20 \rightarrow d=0.08$





Old and new renewables











II



https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA Power Generation Costs 2020.pdf







Wind and solar power are the most credible sources of large amounts of climate-neutral electricity





Summary Electricity

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- can be managed can it?

• Costs of "new" renewables have come down so much that they are the most credible technologies now to provide large amounts of clean electricity (on the timescale to address climate change)

• Partly because of this, electrification of as much energy use as possible must be a cornerstone of climate change mitigation

• But wind+solar power are only a real solution if their variability



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Variability: the problem







Some of the factors that influence demand:

Data: ENTSO-E transparency platform via <u>open-power-system-data.org</u>

- Time of day
- Weekday vs weekend
- Weather (so, seasons)
- Special days like Christmas
- Special periods like vacations



Generation and demand must always be perfectly matched



Adapted from Fig. 6.4 in Blok & Nieuwlaar (2016)

Electricity demand / supply



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"Traditional" power plants



https://www.power-technology.com/projects/maasstroom-energie/



https://en.wikipedia.org/wiki/Electricity_generation#/media/File:Turbogenerator01.jpg



Traditional power system operation



Adapted from Fig. 6.4 in Blok & Nieuwlaar (2016)







Peak load Covered by expensive-to-run plants

Base load Covered by cheap-to-run plants



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Power system with PV and wind





Peak load "Eaten into" by variable renewables



Variable wind and PV



Base load "Eaten into" by variable renewables







Data source: MERRA reanalysis, NASA

Scales of variability



Data source: MERRA reanalysis, NASA

Clouds Local Minutes to hours

Day-night cycle Global 24h

Weather systems Regional Days to weeks

Seasons Continental Months

Climate Global Decades





Time series of wind generation



Data: ENTSO-E transparency platform via <u>open-power-system-data.org</u>





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Data: ENTSO-E transparency platform via <u>open-power-system-data.org</u>





Time series of wind and PV generation



Data: ENTSO-E transparency platform via <u>open-power-system-data.org</u>







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often written as % (0-100)rather than fraction (0-1)

Typical annual averages

Typical capacity factors



Around 10% (in NL) Around 20% (in a sunny place)



Around 30% (in NL)



40-60%



80% (with storage)



80%





Variability: the solutions



We want:



An electricity system with a high share of variable renewable generation (especially solar + wind)



Balancing through space

Three ways to get it:



Storage Balancing through time





Flexibility Balancing by adjusting demand







Grids: balancing through space



More distance = less correlation





Map: https://commons.wikimedia.org/wiki/File:EU-Germany_(orthographic_projection).svg, used under a CC-BY-SA license





Data: Renewables.ninja

Bigger area = smoother output

A wind farm in Bremen

All German wind farms

All European wind farms

Meteorological understanding can improve planning

Concentrate new wind farms on the **North Sea**





Results from the study Grams et al. (2017). *Nature Climate Change*. <u>https://doi.org/10.1038/nclimate3338</u>





Problem: grid expansion



Map: https://commons.wikimedia.org/wiki/File:CHN_orthographic.svg, used under a CC-BY-SA license Photo by Andrey Metelev on Unsplash

few people

3600 th

Not sunny/ many people





Problem: seasonal variability



Summer



Winter







Storage: Balancing through time




How to "store" electricity







Li-ion

Pumped hydro







Batteries (currently Li-ion) are scalable like PV



iPhone 13 Pro battery: 0.012 kWh Rooftop system photo: <u>https://zpenergy.co.za/zpe_projects/15kva-hybrid-inverter-30kwhr-li-on-battery-10kw-solar-pv-sandton-gp/</u> Bulgana photo from <u>https://neoen.com/en/what-we-do/</u>





Raw materials like lithium for batteries



Gold and coal mine photos from Unsplash Lithium mine photo: https://newmobility.news/2017/11/13/sale-worlds-largest-lithium-mine/

Chile

Coal mine China





Hydrogen storage compared to battery storage









PV panels



Seasonal variability

Hydrogen storage compared to battery storage





Large tanks = relatively cheap

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Most attractive storage technologies



Estimation of cheapest storage technology in 2040

Data from Schmidt et al. (2019), <u>https://doi.org/10.1016/j.joule.2018.12.008</u>

Will most likely be hydrogen

> Some possibilities: Compressed air Pumped hydro

Will most likely remain batteries





The "hydrogen vs. electrification" debate





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Liebreich's hydrogen ladder

Unavoidable



Source: Liebreich Associates; @mbliebreich; Re-used under Creative Commons Attribution 3.0 Unported License https://www.liebreich.com/the-clean-hydrogen-ladder-now-updated-to-v4-1/

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Liebreich's hydrogen ladder

Unavoidable



Source: Liebreich Associates; @mbliebreich; Re-used under Creative Commons Attribution 3.0 Unported License https://www.liebreich.com/the-clean-hydrogen-ladder-now-updated-to-v4-1/





Most possible hydrogen applications have better alternatives

Unavoidable



Source: Liebreich Associates; @mbliebreich; Re-used under Creative Commons Attribution 3.0 Unported License https://www.liebreich.com/the-clean-hydrogen-ladder-now-updated-to-v4-1/





Flexibility: Balancing by adjusting demand











Very variable

Somewhat variable







Flexible



Sector coupling: transport + heat





Based on https://www.boell.de/en/2018/04/24/energy-atlas-graphics-and-license-terms?dimension1=ds_energyatlas, CC-BY licensed





More electricity demand — more flexibility?



Based on https://www.boell.de/en/2018/04/24/energy-atlas-graphics-and-license-terms?dimension1=ds_energyatlas, CC-BY licensed



Demand response: smart grid





Traditional grid











Smart grid

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Large-scale: e.g. an industrial plant



Small-scale: e.g. a smart fridge









Balancing through space

- No option alone can solve the challenge
- hydrogen?



Storage Balancing through time

Flexibility

Balancing by adjusting demand

• Short-term variability is basically solved (grids, batteries, flexibility) – long-term variability is harder: might be long-term storage with e.g.





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Share of Modern Renewable Energy,

2009, 2019 and 2020



https://www.ren21.net/gsr-2022/chapters/chapter_01/chapter_01/

Massive capacity growth — but still far from being enough





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Is 100% renewable possible?

Benewable and Sustainable Energy Reviews 50 (2006) 1634-1653

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rse

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

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ARTICLE INFO

Aniale liston's: Received 29 September 2015 Received in revised form 19 February 2016 Accepted 20 February 2016 Accepted 20 February 2016

Reywords: 1006 renewable energy

This study presents one scenario for a 100% penewable energy system in Europe by the transition from a business-as-usual situation in 2000, to a 100% renewable energy Europe for each step, the mean series of steps. Each step reflects one major technological charge. For each step, the mean field by the steps are codered in terms of their scientific and program is decommissioning maker power, implementing a large amount of heat say for each step results indicate that heat pumps, per series with district heating, converting fuel in heavy-duty vehicles to a renew placing natural gas with methane. The results indicate that hy using the Source Program around solve to the additional flexibility that is created by or amount of bioenergy. This is due to the additional flexibility that is created by or the series are anount of bioenergy. This is due to the additional flexibility that is created by or the series of the seri a nous renewable energy system in catope is beenfound positive winner const amount of bioenergy. This is due to the additional flexibility that is treated by o amount or oroenengy. This is due to the additional newtonity that is treated by the heating, cooling, and transport sectors together, which enables an intermittent over 80% in the electricity sector. The cost of the Sourt Energy Europe scenario ever SUS in the electricity sector, the cost of the SMAR Energy Europe section higher than a business-as-usual scenario, but since the final scenario is b instead of imported fuels, it will create appreximately 10 million additional

EXECUTIVE SUMMARY

PREPARED FOR: The National Renewable Energy Laborat A national laboratory of the U.S. Department of Ene

2010

PREPARED BY: **GE Energy**

MAY 2010

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	5. Conclusions Acknowledgements Appendix A. Cost assumptions Beforences

* Corresponding author, Tel.: + 45 9940 2483. E-mail industric devid@plan.acu.clk (D. Cornelly).

http://doi.org/10.0005/j.rser.2016.02.025 1356-0321/e 2016 Elsevier Ltd. All rights reserved.

2016

jobs Europe EnergyPLAN WESTERN WIND AND SOLAR INTEGRATION STUDY:

Energy

()) Ca

Synergies of sector coupling and transmission reinforcement in a costoptimised, highly renewable European energy system T. Brown 4.5, *, D. Schlachtberger ^b, A. Kies ^b, S. Schramm ^b, M. Greiner ^c

ABSTRACT

ARTICLEINFO

2018

Mark Z. Jacobson

2020





Is 100% renewable possible?



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Pathways to implementing this while while navigating social, environmental, and other limits



Challenges: social, environmental, and other limits



'We don't have enough' lithium globally to meet EV targets, mining CEO says

- Current EU-wide building renovation rate ~1% per year
 - If 3% renovation rate from 2027, -77% to -100% EU space heating and cooling energy demand by 2060 possible

Chatterjee et al. (2022), <u>https://doi.org/10.1007/978-3-030-99177-7_7</u>

Wind EUROPE

1 October 2019

New distance rule could rule out new onshore wind farms





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Example from my own research group



Demand for all energy in all sectors across Europe, + industrial feedstocks

Regional distribution of demand: e.g. building heat

Pickering et al. (2022). *Joule*. <u>https://doi.org/jbd7</u>

Technologies for energy supply, conversion, transport, and their possible locations



DC transmission
 Highest initi
 AC and DC transmission
 Model region

supply and demand

Lowest Initial Inter-regional capacity: 0.05 GW
 Highest Initial Inter-regional capacity: 19.80 GW





European energy supply without imported fuels or electricity



Pickering et al. (2022). *Joule*. <u>https://doi.org/jbd7</u>

Not unlike Kornelis Blok's figure!









Algorithm first published: Lombardi et al. (2020). *Joule*. <u>https://doi.org/gg8z6v</u>





Annual primary energy supply (bar) & annual regional PV & wind generation (map)



https://explore.callio.pe/?spore-id::data=376

Regional electricity imports (choropleth) & synfuel production hubs (points)

Transmission capacity expansion (Total: + 0.6 TW)

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Annual primary energy supply (bar) & annual regional PV & wind generation (map)

https://explore.callio.pe/?spore-id::data=341

SPORE 341

Regional electricity imports (choropleth) & synfuel production hubs (points)

Transmission capacity expansion (Total: + 2.8 TW)

	0.00	0.05	5	0.10
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Almost anything is technically possible, but preferences restrict the spatial and technical maneouvering space



Explore the results: <u>https://explore.callio.pe/</u>





- viable and how fast can the transition really be?
- want to question.

• Technically, almost anything is possible — but what is politically

• Studies, reports, scenarios address such questions: often use leastcost optimisation models, and use assumptions that you might



