AN URGENT NEED FOR GRID-STABILIZING INERTIA
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Malta Inc.

On October 18, 2023, the U.S. Department of Energy's Electricity Advisory Committee (EAC) issued a stunning report titled, "Urgent Needs to Reliably Facilitate the Energy Transition."[1] It identifies the crucial need to replace the attributes supplied by retiring, traditional power plants that keep the grid stable, reliable, and resilient. It includes in these attributes: inertia, reactive power capability, energy assured resources, and others. The EAC issued the report "to create a sense of urgency for action … in short order to assure we are not too late to transition reliably into our energy future."

Reliability attributes, like inertia, are the invisible, uncompensated services that keep the grid spinning like a top. The entire grid was designed and built taking their availability as an assumption. They are being lost with the retirement of traditional power plants like coal, gas, and nuclear. While the megawatts of energy they generate can be replaced by variable renewable energy, the essential grid reliability services they offer are not supplied by solar, wind, or batteries, and they are incredibly hard to imitate. Without inertia, the frequency of the grid can become unstable, causing damage to equipment and even collapse of the grid. Fortunately, new technologies such as carbon-free synchronous long-duration energy storage can fill in this gap to ensure a reliable energy transition.

The importance of having inertia

The electric grid has been called the largest machine in the world[2] and the Greatest Engineering Achievement of the 20th Century.[3] Connecting power plants to consumers through a vast network of transmission and distribution lines, it delivers electricity the instant it is needed by families, business, and industries. While it has constantly grown since Thomas Edison connected the Pearl Street Station in lower Manhattan to 59 customers, its basic structure and operating principles have remained the same.

The grid has been engineered to constantly balance the supply and demand of energy, keeping the entire network operating at the same, stable speed. In North America and several other countries, the grid speed is 60 Hz. Europe and much of the rest of the world operate at a grid frequency of 50 Hz. If there is ever, in any instant, more demand for electricity than available supply, grid frequency drops. If supply exceeds demand, grid frequency increases.

The traditional generators operating on the grid – coal, oil, gas, nuclear, and hydropower – all use large machinery, turbines, and generators, that are physically spinning in unison at exactly the same grid speed. Every one of them. If a backup generator is turned on, the first thing it does is spin-up to grid speed and synchronize to the exact speed and phase of every other generator.

Figure 1 Merry-go-round

The spinning metal of each power plant contains its own kinetic energy that keeps it spinning even if plant operation is interrupted. Imagine a playground merry-go-round, with some children riding on the top and others spinning them in a circle. Even when more children jump on, the merry-go-round will continue to spin due to the heft of its spinning mass. The bigger and heavier the merry-go-round, the more consistent the speed.

The synchronous inertia of the spinning metal in all of the connected power plants keeps the grid spinning at 60 Hz (or 50 Hz). Small deviations in load are smoothed out by the synchronous inertia of the system, just like the merry-go-round continuing to spin as children jump on and off. Small changes in load happen all the time, like when temperatures rise, and air conditioners turn on. The grid can handle these

Figure 1. Merry-go-round photo is licensed under the Creative Commons Attribution-ShareAlike 3.0 License. https://en.wikipedia.org/wiki/File:Merry-go-round.jpg

[1] Electricity Advisory Committee. October 18, 2023. Urgent Needs to Reliably Facilitate the Energy Transition. U.S. Department of Energy. https://www.energy.gov/oe/electricity-advisory-committee-reports-and-memos

[2] McBride, James and Siripurapu, Anshu. July 15, 2022. How does the U.S. Power Grid Work? Council on Foreign Relations. https://www.cfr.org/backgrounder/how-does-us-power-grid-work

[3] Wulf, William A. September 1, 2000. Great Achievements and Grand Challenges. National Academy of Engineering. https://www.nae.edu/7461/GreatAchievementsandGrandChallenges

changes on its own, using the rotational inertia of traditional power plants to act as "shock absorbers,"[4] preventing minor fluctuations from compounding into large problems.

A bigger fluctuation risk would be a power plant tripping offline. In a region with 30,000 megawatts (MW) of demand, like the state of Florida, all of the power plants together generate the 30,000 MW of needed electricity. The sudden loss of 1,000 MW of generation – say a large coal plant – would be compensated for by the remaining power plants. The load on the grid would extract the extra 1,000 MW from the inertia of the spinning metal in the operating plants, keeping the lights on until more generation can kick-in.[5] Imagine the unlucky child who trips, falls, and can no longer push the merry-go-round. The merry-go-round's inertia will keep it rotating until another child can run in, catch up, and start pushing.

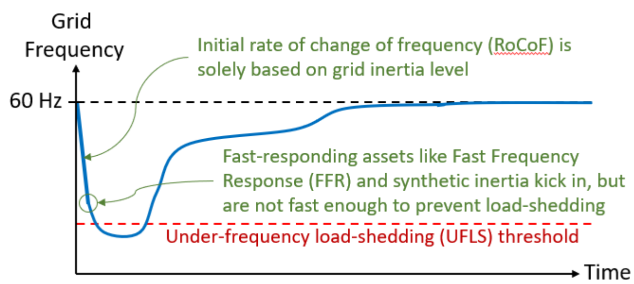

Figure 2 Under-frequency load-shedding

If frequency drops too much – say to 59.5 Hz – utilities must disconnect blocks of consumers, like neighborhoods, to prevent the frequency from dropping further (see figure). A dip in frequency can damage grid equipment, but a drop too low can potentially collapse the entire grid. Disconnecting blocks of consumers to prevent this is called load shedding, and it happens a lot. In the other direction, grid operators can disconnect generators if frequency rises too high, say to 60.5 Hz, because the demand has dropped. This balances the system and, as with the underfrequency case, avoids costly damage to power plants that are designed to operate at grid speed with only minimal tolerance for variance.

Grids on the edge of a stability breakdown

To meet our climate goals, we must transition the grid – also called the bulk power system (BPS) – to net-zero. Clean but variable renewables, like solar and wind, are the fastest-to-deploy and lowest-cost options for replacing the power produced by fossil power plants. However, fossil plants provide more value to the grid than just power – they provide power *on demand* around the clock. Fossil, nuclear, and hydro power plants supply what the Federal Energy Regulatory Commission terms, "ancillary services," and defines them as "those services necessary to support the transmission of electric power… to maintain reliable operations of the interconnected transmission system."[6] This includes synchronous inertia, *the* key attribute in determining how fast grid frequency falls during an imbalance event. To provide these same services, renewables can be paired with new technologies such as grid-synchronous long-duration energy storage (LDES) to provide the same 24/7 reliable power.

Solar power and other inverter-based resources (IBRs) do not provide the synchronous inertia that helps stabilize the grid. Unlike traditional power plants, solar PV generates power as direct current (DC) and requires an inverter to add alternating current (AC) power to the grid. Nearly all inverters are "grid following," meaning they produce AC power at the frequency of the grid they are connected to.[7] If the grid frequency is low, wind, solar, and batteries with standard grid-following inverters will produce AC power at that lower grid frequency, doing nothing to correct the low frequency deviation. Worse, in transmission-constrained areas where the load imbalance results in brownouts (low voltage), grid-following IBRs, like wind, solar, and batteries, can disconnect from the grid to protect themselves, exacerbating an already bad situation. This can result in cascading outages.

The North American Electric Reliability Corporation (NERC) has issued warnings about inverter-based resources for some time. In March 2023 it stated, "These resources have exhibited systemic performance issues that could lead to unexpected losses of BPS-connected generation, with the potential to cause widespread outages. As the penetration of BPS-connected IBRs continues to rapidly increase, it is paramount that any performance deficiencies with existing (and future) generation resources be addressed in an effective and

[4] Wirfs-Brock, Jordan and Paterson, Leig. July 10, 2015. IE Questions: What Keeps Our Electric Grid Humming? Inside Energy. https://insideenergy.org/2015/07/10/ie-questions-what-keeps-our-electric-grid-humming/

[5] Denholm, Paul, Trieu Mai, Rick Wallace Kenyon, Ben Kroposki, and Mark O'Malley. 2020. Inertia and the Power Grid: A Guide Without the Spin. National Renewable Energy Laboratory. NREL/TP-6120-73856. https://www.nrel.gov/docs/fy20osti/73856.pdf

[6] Federal Energy Regulatory Commission. August 31, 2020. Market Assessments: Glossary. https://www.ferc.gov/industries-data/market-assessments/overview/glossary

[7] The Economist. May 7, 2022. Green power needs more than just solar panels and wind turbines. https://www.economist.com/science-and-technology/green-power-needs-more-than-just-solar-panels-and-wind-turbines/21809104

efficient manner."[8] Battery storage, including long-duration flow and iron air batteries, rely on inverters and suffer from the same inadequacy.

A newer technology, dubbed "grid forming" inverters, is intended to mimic certain aspects of synchronous inertia, though NERC stated in September 2023 that their effects must be sufficiently studied before their implementation, and retrofitting may be costly and difficult.[9] The unknowns are numerous, including not just how individual systems behave at a local level, but also how multiple systems interconnected with each other over long transmission lines interact in perhaps unstable ways. Even if all of these unknowns are studied and addressed with sufficient reliability, enabling intermittent renewables and inverter-based batteries to provide *synthetic* inertia might reduce but would not eliminate the need for real *synchronous* inertia.

The grid as we know it has evolved for over 100 years to rely on power plants that provide natural, grid-synchronous inertia. The best providers of this essential service have been large, traditional power plants. Their rotating turbines and generators supply momentum just like children pushing the merry-go-round. In most cases, they are nearly 20 meter long, 300-tonne merry-go-rounds.[10] As an example, combustion turbines, when operating, supply 529 megawatt seconds (MW.s) of inertia per 100 MW of plant capacity.[11]

The good news is that greenhouse gas-emitting power plants are retiring and being replaced with carbon-free generation. The bad news is that the inertia from the retired plants is not being replaced. Grids with the most retirements of fossil and nuclear plants and highest variable renewables penetration are already experiencing inertia-related stability challenges.

The United Kingdom rapidly decarbonized its grid, moving from 2.8% clean power (i.e., wind, nuclear, solar, and hydro) in 2000 to 48.5% in 2022.[12] Of this amount, solar and wind – variable renewables that do not supply inertia – rose to 31.2%; inertia-supplying sources, including nuclear, coal, gas, hydro, and biomass, provided 62.5%.[13] In 2019, more than a million people were impacted by a blackout caused by the 50 Hz system dropping to 48.88 Hz. System inertia was too low to smooth over a wind farm and a gas plant tripping offline sequentially.[14] In 2020, the UK's whole-system inertia was measured to be 197,000 MW.s and was predicted to fall to 119,000 MW.s in 2025. In response to this crisis, the National Grid Electricity System Operator entered into contracts in 2020 to purchase 12,500 MW.s of inertia, or the equivalent of five coal-fired power plants, over six years.[15] It then worked to create a market for inertia. In April 2022, the program purchased another 6,000 MW.s of inertia, and in November 2022 it launched a new phase to purchase an additional 15,000 MW.s.[16]

Australia moved from 8% renewables in 2001-2002 to 32% in 2022; solar and wind accounted for 24% of the mix.[17] In 2017, the Council of Australian Governments Energy Council (now the Energy and Climate Change Ministerial Council) ordered a study of the Australian grid that found that, in 2015 and 2016, synchronous inertia levels in the National Electricity Market (NEM) dropped to their lowest level in five years, and in 2016, the NEM spent more time outside the expected frequency band than acceptable.[18] In response,

[8] North American Electric Reliability Corporation. March 14, 2023. Industry Recommendation: Inverter-Based Resource Performance Issues. https://www.nerc.com/pa/rrm/bpsa/Alerts%20DL/NERC%20Alert%20R-2023-03-14-01%20Level%202%20-%20Inverter-Based%20Resource%20Performance%20Issues.pdf

[9] North American Electric Reliability Corporation. September 22, 2023. Introduction to Inverter-Based Resources. https://www.nerc.com/comm/RSTC/IRPS/IBR_Webinar_FAQ.pdf

[10] Davies, Rob. March 7, 2022. Onward inertia! The secret source for keeping the lights on and greening the grid. The Guardian. https://www.theguardian.com/business/2022/mar/07/onward-inertia-the-secret-source-for-keeping-the-lights-on-and-greening-the-grid

[11] Samuel C. Johnson, Dimitri J. Papageorgiou, Dharik S. Mallapragada, Thomas A. Deetjen, Joshua D. Rhodes, Michael E. Webber. 2019. Evaluating rotational inertia as a component of grid reliability with high penetrations of variable renewable energy, Energy, Volume 180, 2019, Pages 258-271, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2019.04.216

[12] Kyriacou, Georgina and Josh Burke. June 23, 2023. How much do renewables contribute to the UK's energy mix and what policies support their expansion? The London School of Economics and Political Science. https://www.lse.ac.uk/granthaminstitute/explainers/how-much-do-renewables-contribute-to-the-uks-energy-mix-and-what-policies-support-their-expansion/

[13] George, Sarah. January 6, 2023. What did the UK's electricity generation mix look like in 2022? edie. https://www.edie.net/what-did-the-uks-electricity-generation-mix-look-like-in-2022/?regwall=success&register=success

[14] Davies, Rob. March 7, 2022.

[15] Nicholson, Guy. April 4, 2023. Helping the UK Power Grid Spin Back its System Inertia. T&D World. https://www.tdworld.com/digital-innovations/article/21260894/helping-the-uk-power-grid-spin-back-its-system-inertia

[16] Stability Pathfinders: Tendering opportunities for services to enable a zero-carbon system - EnAppSys https://www.enappsys.com/stability-pathfinders-tendering-opportunities-for-services-to-enable-a-zero-carbon-system-2/

[17] Department of Climate Change, Energy, the Environment and Water. 2023. Australian electricity generation - fuel mix. Australian Government. https://www.energy.gov.au/data/australian-electricity-generation-fuel-mix

[18] Office of Australia's Chief Scientist. June 21, 2017. National Electricity Market Reform – A blueprint for the future. Government of Australia.

the Australian Energy Market Commission is attempting to design new market rules to ensure sufficient inertia as more fossil power plants retire.[19]

ERCOT, the islanded grid that encompasses much of Texas, grew its renewable energy mix from 3% in 2007 to 31% in 2023.[20] In 2007, 96% of generation provided grid-synchronous inertia, but in 2023 that number dropped to 61%.[21] In May 2023, the Independent Market Monitor reported to the Public Utility Commission of Texas that the proliferation of "inverter-based generation has also raised concerns on maintaining sufficient system inertia" and "as an increasing share of the load is served by wind, solar, and [non-synchronous energy storage resources], system inertia will continue to fall."[22] ERCOT has been evaluating synchronous inertial response as a potential compensated ancillary service since at least 2016[23] and is presently monitoring system inertia vs. a "critical inertia" threshold of 100,000 MW.s.[24] To ensure grid reliability, ERCOT has relied on previously infrequent out-of-market Reliability-Must-Run (RMR) procedures.[25] Even though it is famous for not having a capacity market, since Winter Storm Uri, ERCOT has shown a willingness to implement out-of-market procurement policies in order to maintain grid reliability. On October 2, 2023, ERCOT issued an RFP for 3,000 MW of capacity for the 2023-2024 winter season to reduce reserve shortage risk.[26] At the same time, if needed, wind and solar will be curtailed in order to maintain critical inertia.[27]

Spain's wind and solar generation grew from approximately 2% in 2000 to 33% in 2021.[28] Not surprisingly, a 2020 study identified a decrease in system inertia as a main concern of system operator Red Eléctrica de España.[29] In July 2021, Red Eléctrica introduced separate interconnection allowances, at each node across the grid, for synchronous vs. asynchronous generation.[30] At multiple nodes, solar PV and other IBRs can no longer interconnect with the grid due to local weakness in the grid caused by lack of inertial resources.

These issues are not isolated and are becoming more prevalent. Small electric grids were studied at the onset of the COVID-19 pandemic when a drop in demand impacted grid frequency. Researchers looked at local grids in Israel, Estonia, and Finland and found that, in times of crisis, natural, synchronous inertia, like that provided by traditional power plants, is necessary to adapt to sharp decreases in demand that impact a small grid's frequency.[31] As renewable penetration increases, grid regulators, transmission system operators, and policymakers will need to be proactive to ensure that grid stability is maintained throughout the transition.

Do two things at once

Islanded grids – those that have few if any connections to neighboring grids – are the canaries in the coal mine of renewables-created grid stability issues. It takes less than you think: U.K., 31.2%; Australia, 24%; ERCOT, 31%; and Spain: 33%. All grids that seek to increase their renewables penetrations while retiring traditional power plants must

https://www.chiefscientist.gov.au/2017/06/speech-national-electricity-market-reform-a-blueprint-for-the-future

[19] Parkinson, Giles. April 13, 2023. Grid inertia: Regulators forced to choose between fossil past and green future. RenewEconomy. https://reneweconomy.com.au/grid-inertia-regulators-forced-to-choose-between-fossil-past-and-green-future/

[20] ERCOT. October 9, 2023. Generation. https://www.ercot.com/gridinfo/generation

[21] Ibid.

[22] Potomac Economics. May 2023. 2022 State of the Market Report for the ERCOT Electricity Markets. https://www.potomaceconomics.com/wp-content/uploads/2023/05/2022-State-of-the-Market-Report_Final_060623.pdf

[23] Future Ancillary Services, Preparing to maintain reliability on a chancing grid. 2016. ERCOT. https://www.ercot.com/files/docs/2016/04/28/FAS_TwoPager_April2016_FINAL.pdf

[24] To Add More Renewables to the Grid, We Need Energy Storage with a Critical Component: Inertia. Renewable Energy World. 2018. https://www.renewableenergyworld.com/storage/grid-scale/to-add-more-renewables-to-the-grid-we-need-energy-storage-with-a-critical-component-inertia/

[25] Reliability-Must-Run Procedures, Determining and addressing the need for generation units to support grid reliability. 2016. ERCOT. https://www.ercot.com/files/docs/2016/06/03/OnePager_RMR_May2016_FINAL.pdf

[26] McGuireWoods LLP. ERCOT Issues RFP to Procure 3,000 MW of Capacity to Alleviate 2023-2024 Winter Concerns. 2023. https://www.jdsupra.com/legalnews/ercot-issues-rfp-to-procure-3-000-mw-of-8808410/

[27] Wold, C. and Snitman, J. 2022 RTP Off-Peak Sensitivity Analysis. August 2022 RPG Meeting. ERCOT. PowerPoint Presentation (ercot.com)

[28] U.S. Energy Information Administration. Spain. U.S. Department of Energy. https://www.eia.gov/international/analysis/country/ESP

[29] Díaz-García, Agustin, Izquierdo, Carlos, Cordón, Antonio, Rodríguez, Francisco, and Rivas, Rosalía. January 05, 2021. Frequency stability model for energy transition studies in Spain. IEEE PES Transmission and Distribution Conference and Exposition, 12-15 October 2020. https://ieeexplore.ieee.org/document/9299984

[30] Red Eléctrica de España. (2021). Dirección General de Operación. Información sobre capacidad de acceso [MW] disponible y ocupada en los nudos de la red de transporte.

[31] Carmon D, Navon A, Machlev R, Belikov J, Levron Y. July 13, 2020. Readiness of Small Energy Markets and Electric Power Grids to Global Health Crises: Lessons From the COVID-19 Pandemic. IEEE Access. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8545327/

implement strategies to ensure the long-term stability of their power systems.

Solar and wind have two major downfalls: intermittency and asynchronicity. Synchronous LDES solutions solve both:

1. They are load-following, converting renewables from intermittent resources into "firm," 24/7, base-load power; and
2. They are grid synchronous, supplying like-for-like replacement of the essential reliability services lost with the retirement of traditional power plants.

Firming renewables is critical to accelerating the deployment of wind and solar power. LDES eliminates the real and perceived challenge of intermittency in solar and wind. Gone will be the "the sun doesn't shine at night" comments when LDES converts intermittent plants into 24/7 power. LDES also improves the economics of renewables projects: by storing surplus power that would otherwise be curtailed and using it to fill in generation gaps, LDES maximizes the return on investment of intermittent technologies and reduces their cost per kilowatt-hour. Storage also facilitates the interconnection of more variable renewables on existing transmission lines by ensuring the lines run at optimum capacity rather than risking overloads. By improving the efficiency of our existing T&D system, large investments in new buildouts can be deferred or displaced.

More importantly, grid synchronous LDES – like Malta's Clean Power Plant – supply essential ancillary services, like synchronous inertia, reactive power voltage regulation, short-circuit current, and others. These capabilities will unlock the full potential of solar and wind, allowing them to fully replace the services supplied by fossil power plants and speeding their deployment without threatening the stability of the grid.

Malta's Clean Power Plant provides more synchronous inertia than competitive LDES technologies and is a like-for-like replacement for the inertia lost with retiring fossil generators. The figure below shows the inertia of the Malta Clean Power Plant in comparison to traditional generators.

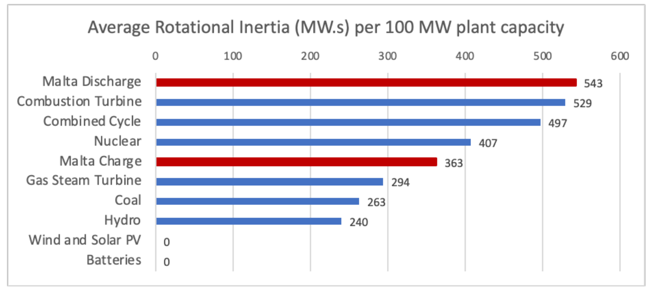

Figure 3: Average rotational inertia for different generator types[32] shown alongside Malta Clean Power Plant inertia during charge and discharge

<u>What's next?</u>

On October 24, 2023, the International Energy Agency issued a stark warning about the world missing the 1.5˚C climate change milestone: "a pathway to limiting global warming to 1.5 °C is very difficult – but remains open."[33] To keep global warming to 1.5˚C by 2050, the IEA predicts we will need to increase the share of global energy supply generated by solar and wind to a cumulative 33% by 2030 – in six years.[34] We know with certainty from grids today that this level of variable renewable energy penetration, without further action, will threaten the stability of the grid.

We don't have any other options to deploying necessary amounts of solar and wind by 2030. They are carbon free and the lowest cost generation available today. Alternatives, like carbon capture, hydrogen, small modular nuclear reactors, and other nascent technologies, won't be ready in time to make up the difference.

The EAC identified a "pacing mismatch" between retirement of traditional power plants and deployment of solar, wind, and batteries.[35] It called for careful consideration of regulatory policy and timely and bold action to assure the level of reliability that is necessary to decarbonize our grid rapidly. Action "must be taken soon to assure we are not too late to transition reliably into our energy future." Now is the time to deploy technologies that allow vastly more solar and wind to be deployed without jeopardizing the stability, reliability, and resiliency of the power grid.

[32] Johnson, Samuel C., Dimitri J. Papageorgiou, Dharik S. Mallapragada, Thomas A. Deetjen, Joshua D. Rhodes, Michael E. Webber, Evaluating rotational inertia as a component of grid reliability with high penetrations of variable renewable energy, Energy, Volume 180, 2019, Pages 258-271, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2019.04.216

[33] International Energy Agency. October 2023. World Energy Outlook 2023. https://www.iea.org/reports/world-energy-outlook-2023

[34] International Energy Agency. September 2023. Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach. https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach

[35] Electricity Advisory Committee. October 18, 2023.