United Nations
ECE/ENERGY/GE.5/2023/5

Economic and Social Council

Distr.: General
25 July 2023

Original: English

Economic Commission for Europe

Committee on Sustainable Energy

Group of Experts on Cleaner Electricity Systems

Nineteenth session
Geneva, 3-4 October 2023
Item 6 of the provisional agenda
Achieving net-zero emissions power systems

Transitioning to net-zero emissions power systems – common principles for reliability of supply

Note by the secretariat

Summary

Achievement of the established laudable environmental goal of reaching net-zero carbon dioxide emissions globally by 2050, requires fundamental changes in how the different sectors of the economy are structured and operated, and will accelerate changes in resource management, supply chain, end use consumption, and conversion technologies. These changes will take extraordinary and determined action.

Electrification is one of the means to reduce emissions from many activities, provided that the growing electricity sector simultaneously transitions to low, net-zero and net-negative carbon dioxide emission generation technologies eventually followed by additional carbon dioxide removal as necessary.

The present document was developed by the Group of Experts on Cleaner Electricity Systems in support of the activities of the Committee on Sustainable Energy. It explores the risks, during the necessarily rapid expansion and transition in the electricity supply system, of possible unintentional losses in system reliability, and discusses the issue of retention of sufficient dispatchable capacity amid transitioning to net-zero emissions electricity systems, to maintain grid reliability and resilience.

I. Introduction

1. The established laudable environmental goal to reduce the risk and impact of climate change induced by greenhouse gas (GHG) involves the aim of reaching net-zero carbon dioxide globally (i.e., cutting emissions to as close to zero as possible, with any remaining emissions re-absorbed from the atmosphere) by 2050, which is slightly less than 10,000 days away. Timely achieving this will require fundamental changes in how the different sectors of the economy are structured and operated, and will accelerate change in resource management, supply chain, end use consumption, and conversion technologies. These changes will take extraordinary and determined action.

2. One of the major pathways to a net-zero future is to electrify many end uses of energy that currently use fossil fuels directly, with a consequent growth in electricity generation notwithstanding improvements in end-use efficiency. Short term electrification priorities include electric mobility (e-mobility) and advances in the building sector, two of the largest energy end use areas. But, for electrification to be effective in reducing emissions, this growing electricity generation sector has simultaneously to transition to low, and then net-zero, GHG emission sources, eventually followed by carbon dioxide removal as necessary to achieve net-negative CO_2 emissions.[1] The international financial community is working to further accelerate this transition through Environmental, Social and Corporate Governance (ESG) policies governing their lending practices on regional and national levels.

3. Accordingly, policies are being put in place in many jurisdictions in the United Nations Economic Commission for Europe (ECE) region to promote the rapid deployment of renewable technologies, especially wind and solar, on the broadest possible scale along with investments in emerging technologies to enable energy storage (including, but not limited to, hydrogen and various energy storage options) to support these policies. New nuclear generation, and fossil and biomass generation with carbon capture and sequestration (CCS), are also being developed in some ECE member States.

4. Once non-fossil generation sources such as wind, solar or nuclear are built, their zero or low marginal operating costs mean that their electricity output, when available, will naturally displace fossil generation, both with and without CCS, due to fundamental economics. Similarly, CCS power plants will have lower marginal operating costs than conventional, unabated, fossil fuel plants at even moderate levels of carbon emission pricing [2] and can be expected to be operated in preference to unabated generation when required.

5. Additional ‘top down’ restrictions on fossil fuel (oil, coal, and natural gas) use for electricity generation, such as forced plant closures, are, however, also being considered. These measures will obviously tend to further restrict the amount of fossil fuel use, but they will also reduce the amount of dispatchable generation capacity available to meet demand when there are no other options. Typically, this will require only limited periods of operation and, as more non-fossil generation and supporting energy storage infrastructure are deployed, these periods will become shorter.

6. A resilient energy system is the one able to withstand and recover from an unforeseen event. The Committee on Sustainable Energy (the Committee) at its thirty-first session (21-23 September 2022) also argued that a resilient energy system is the one where energy makes an optimal contribution to a country's social, economic, and environmental development while striking a balance between sustainability, affordability, and security.[3] However, unless sufficient electricity capacity is retained to meet whatever demands are placed on the supply system, there is a risk of not meeting the security and also the affordability components of a resilient energy system. At the current stage in the electricity sector transition the question resolves into retaining fossil fuel capacity until it is gradually

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[1] See: https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf

[2] The carbon price to make marginal costs for fossil generation without CCS more expensive is much lower than the carbon price required to cover the full costs of CCS, including capital investments.

[3] See: https://unece.org/sed/documents/2022/09/post-session-documents/final-report-thirty-first-session-committee

replaced by alternatives. The concern is, therefore, that the combination of policies being adopted by member States to reduce GHG emissions of the electricity generation sector and simultaneously to increase electricity use, do not result in unintentional, and unacceptable, losses in system reliability.

7. Meeting electrical energy needs at all times is a priority; until large scale and long duration electricity and other energy storage options are actually in place, the electric grid will require a significant amount of generation capacity that is dispatchable (i.e., able to produce energy on demand, with high confidence of availability under all circumstances). But in addition, and often not so readily appreciated, a stable electric grid will require a series of essential reliability services such that it can maintain frequency, voltage, and ramping across a wide variety of operating conditions. Finally, as more variable energy resources such as wind and solar are added to the grid, the ability of dispatchable power generation to ramp up and down quickly becomes critical to balancing the production of these less certain low carbon resources.

8. Fossil fuel generation currently provides the majority of these essential grid reliability services. Such power generation plants are available when needed to be dispatched, to provide inertia (necessary to resist changes in grid alternating current frequency resulting from system faults and to minimize the effects of grid disturbances), and to generate reactive power (necessary to maintain voltage). At least in the case of natural gas, fossil plants can also ramp up and down very quickly to balance the variability of wind and solar generation.

9. It is particularly noted that, while a radical increase in future electricity use is essential, the future demands that this expansion will place on electricity supply systems, are inevitably not immediately apparent in today's grids and even less in all previous experience of largely fossil-based electricity grid operation and in the recent experience, in a number of regions, of stability or decline in electricity demand. Thus, based on experience that will soon be out of date, an accelerated retirement of fossil-fuel-based generation capacity may be deemed feasible, and actually occur and be irreversible, without the reliability services this generation provides, essential to the reliable operation of an enlarged electricity grid, being replaced by alternatives that can be used in the future. In addition to direct restrictions, retirements are being driven, in some cases, by distorted price signals that do not represent the value of all the services provided and also by the significant capital needs to comply with proposed environmental regulations. Such retirement dynamics of fossil-fuel-based generation assets are observed in several ECE member States.

10. The ECE Group of Experts on Cleaner Electricity Systems (the Group of Experts) argues, however, that the retention of sufficient dispatchable capacity to provide these needed services until alternatives are actually in place is obviously critical to maintain future reliability and resilience of the grid. This retention need not be in conflict with carbon reduction goals. Fossil fuel consumption and associated CO_2 emissions will inevitably decline as the low or zero marginal operating cost of low carbon sources of generation become available, as described above. But, when needed to balance the system and to address shortfalls in renewable energy production, a backup generation capacity, often fossil-fuel-based, until alternatives are introduced, will be extraordinarily valuable. Retaining the appropriate levels of dispatchable capacity (including fossil-based, operating at much lower capacity factors), perhaps while converting to lower carbon emitting fuels such as natural gas, provides a series of resilience benefits that must otherwise be replaced by other technologies to maintain the continued reliable operation of the Bulk Power System. This includes resource availability for black start capability.

11. Accordingly, the Group of Experts urges member States to consider the consequence of carbon reduction policies on conventional, unabated, dispatchable fossil generation capacity and to find ways to maintain that capacity until its energy and reliability services are demonstrably replaced through a combination of large scale long duration electricity storage for on-demand supplementary energy supply, smart "grid forming" inverters for grid frequency and voltage control and, where consistent with national policies, fossil fuel plants with CCS that can offer similar grid services. Electricity storage could come in the form of naturally inertial physical storage technologies such as pumped hydro, compressed or liquid air energy storage, or other physical storage systems as well as chemical storage (batteries), although these non-fossil grid security technologies are nascent and largely not available at

scale and may be physically limited. Other energy storage, such as heat, could also reduce peak electricity demand. Fossil fuel generation could have CCS applied at source or, especially for plants that are used infrequently, could have the emitted CO_2 recaptured from the atmosphere using direct air carbon capture and storage; again, these technologies are nascent and, in the case of point source CCS, have limits on where they can be applied.

II. Issues and challenges

The scale of the electrification transformation is enormous

12. Full electrification of the economy would require a massive increase in the scale of the electricity grid – a daunting challenge given the capital intensity of electric power generation, transmission, and distribution. Load growth forecasts are already starting to show annual increases; in North America, for instance, these increases reach 7-10 per cent after a protracted period of very modest growth due to energy efficiency programmes.

13. In order to achieve renewable portfolio targets set by various regulators and policymakers, within the past decade the electric power utilities have aggressively integrated low- and no-carbon generation resources into the electric grid. These policy decisions, along with reductions in the cost of inverter and photovoltaic (PV) panel technologies, have made commercial investments into renewable variable energy resources (VERs) very attractive, reaching over 60 per cent of total investment. Further, consumers are incentivized to install rooftop solar generation and also to participate in demand-side management programmes that include both energy efficiency and demand response.

14. With this accelerated integration of zero marginal cost VERs, dispatchable generation is being forced “out of the market” and running substantially less frequently. Faced with significant investments for environmental retrofits and maintenance and lacking any other revenue streams to compensate for the reliability services they provide to the grid, many asset owners are choosing to retire fossil capacity and, with these retirements, the entire present electricity grid is losing reactive power frequency response and ramping. Replenishment of these characteristics is critical to stable grid operation, especially during system events and disturbances.

Energy supply security needs are increasing

15. Continuity of electricity supply creates certainty so citizens can be assured that they will have the electricity to meet their energy needs, without the need for private backup supplies (e.g., firewood, standby generators, domestic batteries, etc.). This continuity is vital to modernizing an economy and encouraging reliance on it for electrification of transport, heating, etc. and, as the grid is transformed and expanded, this continuity of supply must be even more strongly sustained to assure energy demands are met. The very nature of solar and wind is that their output is variable, with their dependence on environmental conditions. Alternative sources of energy are needed for when conditions occur that reduce the output from large amounts of these resources.

16. Electricity providers can invest in demand-side management (energy efficiency and demand response), but there are limits to the scale and duration or persistence of response when long-duration extreme weather events are experienced, and energy is needed to address basic societal needs. Therefore, with the focus on decarbonization through electrification of all types of energy applications, continuity of supply becomes ever more important. If there are going to be any electricity supply reductions, it is important they are planned; since with planned reductions, citizens can make additional preparations, but with unplanned interruptions in supply they can be left stranded with energy deficits, and potential harm. For example, over the past two decades with the rise of internet-based commerce, expansion of internet-based telecommunications, and the digitization of multiple aspects of society (internet of things, entertainment, etc.), tolerance for supply interruptions, even if momentary, is declining rapidly. With an expansion of end uses of electricity, that tolerance will likely drop to near zero, thus reliability performance will need to improve.

17. As neighboring interconnected grids often experience similar weather and climatic conditions, the ability of transfer capacity to provide high levels of energy security is limited;

its main role is to maximize competition and reduce energy prices day-to-day. Therefore, it is argued that currently, the primary technologies required for energy security, are largely fossil-based generation plants with CCS (or low emissions plants, such as hydrogen-fueled), large hydro, and large-scale long-duration energy storage units.

Dispatchable capacity is essential but already under pressure

18. Until cost-effective energy storage solutions are deployed at large scale and with significant, multi-day duration, electricity will continue to need to be produced mostly when it is consumed. While wind and solar have complementary production profiles in many areas, they are nowhere near perfectly inversely correlated and require a certain amount of highly flexible and dispatchable generation to balance renewable electricity production.

19. This dynamic is placing significant stress on the fuel supply system in areas with very high PV penetration; as loads continue to build in the late afternoon and evening and solar generation declines as the sun sets, dispatchable natural gas generation needs to ramp up rapidly to fill the gap. This afternoon ramp pulls gas out of the local gas distribution system faster than the pipelines can supply it, increasing the need for natural gas storage as a buffer.

20. While short (e.g., four hour) duration batteries are able to make an important difference in managing the speed of this ramp, abated natural gas generation and long duration storage would be key technologies for being able to meet peak requirements without using conventional fossil-based plants. Other critical infrastructure industries use significant amounts of electricity. Steel recycling, for example, uses electric arc furnaces that require instantaneously significant amounts of electricity for short periods of time two or three times per hour (10-15 minutes bursts). This type of electricity can only be provided by dispatchable electric sources. Not being supplied with the electricity when needed could lead to equipment failure.

‘Common conditions’ can impact large amounts of renewable generation

21. Measures to ensure electricity grid reliability are based on the concept of independent random equipment failures in generation and transmission facilities – this is what gives rise to the concept of a reserve margin. However, as already noted, wind and solar (and even hydro) are impacted by wide area ‘common conditions’ that do not apply to dispatchable generation resources. Multi-day thick cloud cover, fog, or smoke that impact solar, or ‘wind droughts’ occur frequently, while water drought conditions have limited hydroelectric generation in areas such as the Western United States for years at a time and the whole of Europe in 2022.

22. To provide resilience against such conditions without the use of fossil fuels would, as described above, require a variety of zero-carbon generation technologies and energy storage with durations of days and weeks, capabilities not currently provided by available energy storage such as batteries. Physical storage technologies such as pumped hydro, compressed or liquid air energy storage could help meet scale requirements but they still rarely would have the duration needed to supply a full load for multiple days.

Essential reliability services must be provided

23. A reliable synchronous electricity grid requires more than just energy to operate reliably and stably. The electricity grid must maintain voltage and frequency within very tightly defined parameters. A number of key reliability services are naturally provided through conventional synchronous “spinning mass” generation using steam and gas turbines, such as reactive power to maintain voltage, frequency response, and ramping flexibility to offset intermittency of VERs.

24. By contrast, inverter-based resources (IBRs: solar PV, wind, and batteries) do not inherently produce any of these services as they rely on power electronics to interface with the grid. There are examples of reliability issues with inverter resources, most resulting from integration challenges and the lack of good modeling. Their behavior is therefore not always fully understood, and control systems require tuning in different ways than for synchronous machines. In 2017, the United Kingdom experienced a widespread loss of wind and solar generation and there have been multiple grid reliability events in the United States driven by PV inverter behavior, the most recent being a loss of 1,700 MW of solar, which precipitated

an additional 800 MW loss of natural gas generation in West Texas and almost triggered rolling blackouts from the grid operator to prevent under-frequency load shedding.

International standards for IBRs are necessary but not yet fully developed

25. As IBRs continue to grow on the electricity grid, international standards governing their grid support performance and modeling for their behavior will be essential. A number of standards developed by Institute of Electrical and Electronics Engineers (IEEE) [4,5] have recently been promulgated, but more work is needed to ensure the fullest possible replacement of conventional generation services. Until such standards are in place and performance attributes established, IBRs will operationally be "black boxes" on the electricity grid and will create the risk of magnifying small disturbances into major reliability events.

Conventional grid reliability assets may not be supported to remain in place until alternative, replacement technologies are actually built and operational

26. With more renewable resources, uncertainty about the ability to generate and deliver electricity increases, especially in the case of some long-term, widespread environmental conditions. To assure continuity, these uncertainties cannot be adequately addressed by backup supplies with the typical battery operating duration of 4–8 hours. Dispatchable generation assets or long duration storage, which provide high levels of certainty and continuity of supply, need to be available to offset the uncertainties from variable renewable energy. Currently, those assets are nuclear, hydro, biomass and fossil-fuel power stations coupled with inertial storage where available, and a fleet of these generating resources is needed to address these uncertainties and to guarantee continuity of electricity production and delivery for the foreseeable future – although not necessarily indefinitely.

27. However, retention of existing dispatchable assets or their replacement with alternatives over the next twenty years is complicated because:

(a) The rapid expansion of renewable generation with its zero marginal cost production is pushing synchronous dispatchable generation, and its much-needed associated reliability service contributions, out of the supply stack of operating units;

(b) Energy, and even capacity, markets are failing to properly price the full range of reliability services provided by different forms of generation. As a result, many merchant power generators fail to make investments to improve their reliability performance (for example, weatherization investments or investments to firm up and secure fuel supply);

(c) Balancing capacities and inclusion for individual energy producers such as small-scale solar parks selling energy to common grid, e.g., NordPool. Restrictions and price limits are impacting a potential increase of private investments into renewable energy generation. For instance, by 2030 over 100 million households may rely on rooftop solar PV;[6]

(d) Other policies not directly associated with electricity supply, for example, new environmental requirements for existing plants that would require significant capital investment to meet, are also driving investors to retire and decommission synchronous dispatchable generation sources, especially coal, oil, natural gas and liquefied petroleum gas as well as nuclear generation.

CCS technologies need to be deployed and developed if they are to be available for widespread use

28. Power CCS deployment at scale, including on natural gas as well as coal, needs to take place for learning by doing to improve key factors such as rates of CO_2 capture, operational flexibility, the inevitable energy demand imposed by capture equipment on the host power station, equipment and process reliability, and CO_2 transport and storage costs and potential hazards. Successful reference projects are essential to enable widespread and

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[4] See : IEEE SA - IEEE 2800-2022, https://standards.ieee.org/ieee/2800/10453/

[5] See : IEEE SA - IEEE 1547-2018, https://standards.ieee.org/ieee/1547/5915/

[6] See: https://www.iea.org/reports/approximately-100-million-households-rely-on-rooftop-solar-pv-by-2030

cost-effective roll-out of CCS and carbon capture, use and sequestration (CCUS) technologies, which in turn is needed if fossil-based power stations (with all their attendant inherent benefits for energy security, grid operation and system reliability) are to play a substantial role in a net-zero energy system.

III. Recommendations for member States, and expected outcomes

29. The foregoing proved possible to formulate the following recommendations for ECE member States on common principles for ensuring reliability of power supply while transitioning to net-zero emissions systems:

(a) Remove unnecessary constraints: getting to a net-zero, resilient and enlarged electricity grid is extremely challenging. Member States should focus on the outcomes that actually matter: CO_2 emissions, electricity supply security, and costs for electricity users, noting big differences in methods within ECE but common principles;

(b) Evaluate generation assets using more than their energy cost per MWh, or even their contribution to balancing real-time energy supply and demand. In realistic resiliency situations (e.g., extreme weather, conflicts), it must be ensured that the grid has frequency response, reactive power, and ramping within desired parameters. It must also be recognized that remuneration based solely on energy production (MWh output) misses key aspects of power plant reliability services essential to the stable and reliable operation of the grid:

(i) “Energy-only” markets do not compensate all of the services that are provided (and required) for grid operation;

(ii) There is a clear need for additional revenue streams, pricing structures, or regulatory requirements to ensure that the full suite of reliability services that are required to operate an alternating current electricity grid, are provided.

(c) Identify existing strategic assets that are critical to the grid’s stable and reliable operation and do not mandate their removal until their services are adequately replaced or it is proven that they are no longer needed, including for the future expansion of electricity supplies as part of wider electrification;

(d) Continue to push for rapid deployment of renewable generation, energy efficiency and demand side technologies, and make maximum use of renewable resources and other low and zero carbon technologies (including nuclear, in line with national goals and developmental aspirations) to reduce the carbon footprint of the sector;

(e) Support development and deployment of long duration (i.e., multiple days to weeks) energy storage solutions;

(f) Since it is difficult to imagine the electricity grid operating reliably without some amount of available on-demand ‘emergency’ power generation, which will most likely be based on fossil fuel, it is critical that advances in direct air carbon capture and storage as well as point-source carbon capture (use) and sequestration technologies be aggressively pursued, since engineered capture of the emitted CO_2 from the atmosphere and its permanent, safe sequestration may be the cheapest and most flexible way of achieving net zero carbon footprint of the dispersed and infrequent use of fossil fuels;

(g) In addition to ‘emergency’ fossil use directly for electricity generation, recognize that fuels (e.g., natural gas) can still play important roles in supplying large amounts of energy over short periods for end users in the near- and medium-term, which otherwise would require a significant increase in electricity generation and transmission capacity that would be used only infrequently and increase redundancy.[7] An example is the

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[7] ECE/ENERGY/143 (https://unece.org/sed/documents/2022/09/post-session-documents/final-report-thirty-first-session-committee) defines redundancy as spare capacity within a system, such as duplicate components, assets, or functions, that increases the reliability of a system to avoid disruption. In the energy sector, redundancy can include local backup power generators or storage systems, idle capacity in transmission and distribution networks, or idle generating assets.

use of supplemental fuel for space heating to extend the performance of heat pumps at extremes of ambient temperatures and when VRE output is low; in such circumstances local direct combustion for heat generation can be both more effective and also reduce electricity generation and transmission demand, even taking into account the need to use direct air carbon capture and storageto recapture the associated CO_2 emissions to achieve net-zero operation;

(h) Prepare for a transition to net zero when investing by specifying assets suitable for future net-zero grid roles (e.g., make new fossil generation capacity flexible and with CCS, or reliably CCS-ready). Also, advance the development of long duration high-capacity energy storage to eventually enable the grid to operate with little or no fossil-based backup;

(i) Member States should also come together with the engineering community to develop common international standards for the reliable operation of IBRs, which will undoubtedly provide the majority of the energy in the grid;

(j) Since estimates suggest that cities are responsible for 75 per cent of global CO_2 emissions,[8] member States should enhance cooperation with municipal authorities and larger urban areas, creating a stronger link with their Sustainable Energy Action Plans to foster investments towards net-zero transitions and to ensure energy grid resilience for both critical infrastructure and end-users.

30. The result will be continuing progress toward a much larger electricity grid, that as well as having progressively lower CO_2 emissions, and eventually becoming net-zero, will continue to operate reliably and so build the necessary consumer confidence in security of supply and affordability to support rapid substitution of electricity for direct use of hydrocarbon fuels. Though much fossil fuel generation capacity will by necessity remain (until breakthroughs in energy storage technology are achieved), it will run much less and only when needed, ensuring substantially reduced emissions from the sector. This is analogous to a plug-in hybrid electric vehicle, which runs predominantly on electricity but can operate on petrol when necessary.

31. The Group of Experts also notes that retention of certain key fossil generation assets may help supplier communities and provide a more just transition through job preservation. Even though those assets will likely be generating much less energy (and concomitant carbon emissions), they will still be providing high-value reliability services.

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[8] See: https://www.unep.org/explore-topics/resource-efficiency/what-we-do/cities/cities-and-climate-change