Increasing Penetration of Variable Renewable Energy: Lessons for Asia and the Pacific

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Kapil Thukral, Principal Evaluation Specialist, Sectors and Projects Division, Independent Evaluation Department (kthukral@adb.org); Priyantha Wijayatunga, Director, Energy Division, South Asia Department (pwijayatunga@adb.org), Susumu Yoneoka, Energy Specialist (Smart Grids), Sustainable Development and Climate Change Department (syoneoka@adb.org). We dedicate this paper to Alan Douglas Poole who passed away during its preparation. His knowledge and original ideas regarding variable renewable energy were the key source of inspiration for the team to work on this paper. Former Director General Vinod Thomas and the present Director General Marvin Taylor-Dormond guided the paper. The paper benefited from inputs from Alex Perera of the World Resources Institute and Kelly Hewitt (formerly with the Independent Evaluation Department), who reviewed an earlier draft of the paper. The team thanks the Editorial Committee comprising Veronique Salze-Lozac’h (Deputy Director General, Independent Evaluation Department), Gil-Hong Kim (Senior Director concurrently Chief Sector Officer, Sustainable Development and Climate Change Department), Hans Van Rijn (Principal Evaluation Specialist, Independent Evaluation Department) and Dae Kyeong Kim (Senior Energy Specialists – Smart Grids, Sustainable Development and Climate Change Department) for their quality review. The team also thanks Irene Garganta and Charina Mendoza Regodon for their administrative support.

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ABSTRACT

Variable renewable energy (VRE) technologies that harness solar, wind, and other intermittent energy resources are among the front runners for mitigating climate change. However, the timing and level of power generated from VRE installations depend on resource availability and are independent of the variations of power demand. VRE output is intermittent and comes with a low marginal cost. This unique combination of VRE characteristics will increasingly influence power system design, performance, and economics as VRE penetration increases. This paper discusses approaches for reducing and managing the mismatch between power supply and demand as VRE penetration increases. In so doing, it refers to policies and regulations, technology choices and investments, and operation and maintenance (O&M) practices. It makes suggestions for the Asian Development Bank (ADB) and its client countries from experience gained worldwide, in line with ADB’s Energy Policy.

Keywords: variable renewable energy, small power systems, large power systems, power market structure, balancing power supply and demand, generation flexibility, energy storage, demand response, grid flexibility, smart grid
EXECUTIVE SUMMARY

Variable renewable energy (VRE) technologies that harness solar, wind, and other intermittent energy resources are among the front runners for mitigating climate change. Many countries, including ADB client countries, have set aggressive VRE targets for mitigating climate change. Along with declining VRE price trends, this means that grid management services will become increasingly important as VRE penetration increases. Although the grid integration objective has gained ground in recent years, most ADB supported projects are still in their early stages and provide few firm lessons to date.

Lessons learned from experience world-wide show that the following will facilitate VRE integration in existing and expanding power systems:

- a suitable regulatory framework
- a more flexible generation capacity
- energy storage capability
- demand response
- enhanced grid flexibility
- smart grid technologies

These measures are consistent with ADB energy policy and can broaden the repertoire of ADB interventions. It is useful to distinguish between small and large power systems particularly when VRE generation shares are significant and on the rise, as small power systems offer relatively fewer options compared to large power systems for maintaining smooth operations. To date, ADB supported projects have introduced a few approaches to facilitate grid integration of VREs. In addition to grid strengthening and grid extension—among the traditional areas of ADB’s power sector interventions—ADB has supported projects that include:

- battery storage in small island developing states (SIDS) and other countries
- demand response from selected consumers to time-shift loads in SIDS
- capacity building and investment in some smart grid technologies in countries with large power systems
- policy and regulatory support, which has been largely with the objective of providing a level-playing field to VRE developers and operators.

ADB must continue to support these approaches, as appropriate, in SIDS and other countries.

Some of the notable omissions that ADB can consider supporting (where relevant) are the following:

- a suitable power market structure
- increased flexibility of power generators
- demand response programs which can possibly be combined with energy efficiency programs
- large-scale energy storage

There can be situations where with increased flexibility of an existing thermal power unit, CO₂ emissions per unit of generation from the particular thermal unit increase while CO₂ emission reduce system-wide. In such situations, ADB could consider supporting increasing the flexibility of existing thermal power units. Likewise, and subject to all environmental, social, and other considerations (including safeguards), ADB could support modifications in conventional and pumped storage hydropower facilities for utility-scale energy storage.

Although ADB has supported interconnections between two or more power systems—mostly within a country but also across international boundaries—the stated rationale has never related to exploiting spatial grid flexibility benefits of VRE. Yet, it is clear that VRE complementarity over a reasonably wide geography provides a good rationale for strongly interconnecting grids for synchronized operation. This can contribute to achieving ADB’s targets for supporting climate change mitigation and is consistent with the rising concerns over global and regional public goods.

All these measures are compatible with the current ADB energy policy, and will become increasingly important as VRE investments grow. Policy dialogue must begin sufficiently early so as not pose a binding constraint that curtails VRE output or impedes investment in VRE capacity.
I. INTRODUCTION

1. Variable renewable energy (VRE) technologies for harnessing solar, wind, and other intermittent energy resources are among the front runners for containing carbon dioxide (CO2) emissions and mitigating climate change. However, the timing and level of power generated from these technologies depends entirely on resource availability, independently from the variations in demand. This exclusive supply-side orientation of VRE power generation poses difficulty in integrating VRE\(^1\) into power systems\(^2\) as VRE penetration increases.

2. This working paper discusses approaches for reducing and managing the mismatch between power supply and demand as VRE penetration increases. In so doing, it refers to policies and regulations, technology choices and investments, and operation and maintenance (O&M) practices. It draws lessons for Asian Development Bank’s (ADB’s) client countries from the experience gained worldwide in operating power systems where a high share of energy comes from VRE resources. The paper aims to contribute to refining ADB’s approaches for facilitating high VRE penetration in power systems in its client countries.

A. Context: VRE grid management services are key

3. The outlook for VRE, including price trends and commitments of ADB client countries, show that grid management services will become increasingly important in these countries as VRE penetration increases.

   1. VRE will become more prominent

4. As per Climate Analytics (2015) estimates, the long-term goal of limiting the rise in the mean global temperature to within 2°C from pre-industrial levels can be achieved if global greenhouse gas (GHG) emissions fall 40%–70% below the 2010 levels by 2050, and reach zero during the 2080–2100 period. Given that energy production and use account for two-thirds of the world’s GHG emissions, global energy-related CO\(_2\) emissions need to decrease by 35%–80% below 2010 levels by 2050 and reach zero during 2060–2075. Such deep emission reductions call for reducing the energy intensity of the global economy and carbon intensity of power generation.\(^3\)

5. The deployment of renewable energy is widely considered as one of the major planks for low-carbon development. Renewable energy technologies play a prominent role in the International Energy Agency’s (IEA’s) proposed bridge strategy that could help achieve an early peak in total energy related GHG emissions at no net economic cost. As per IEA (2015), the proposed bridge strategy calls for boosting investment in renewables-based power generation technologies from $270 billion in 2014 to $400 billion in 2030.

6. The vast array of renewable energy technologies that are being considered today includes (i) geothermal, biomass, and waste-to-energy power generation options that are typically dispatchable; (ii) hydropower options with large storage capacity that are dispatchable; (iii) run-of-river and micro hydropower options that typically show significant seasonal variations in generation; and (iv) VRE

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\(^1\) Such integration is distinct from interconnection of VRE to an existing grid, which of course, is required for any grid-connected VRE capacity.

\(^2\) In this paper, power system refers to a network of electric components served by a single control center that monitors system conditions and schedules generation dispatch.

\(^3\) There have been some encouraging signs. Some decoupling between economic growth and energy consumption (and related CO\(_2\) emissions) is evident. Significant mitigation efforts in developing countries and emerging economies have contributed to this outcome, even while their economic growth rates have continued to increase energy demand and use.
technologies, using energy sources such as solar and wind, which have substantial variability within a 24-hour cycle and are non-dispatchable.

7. The limited potential of other renewable resources means that VREs would become increasingly important in the coming years in providing the required levels of energy—whether in terms of VRE share of power generation in total power generation (from all power sources) or in all renewable energy applications. This is evident from Figures 1 and 2, which depict the renewable energy scenarios prepared by IEA and the International Renewable Energy Agency (IRENA), respectively.

**Figure 1: Rising Shares of Variable Renewable Energy based Power in Total Power Generation**

<table>
<thead>
<tr>
<th>Year</th>
<th>VRE</th>
<th>Other RE</th>
<th>Other power sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>2%</td>
<td>18%</td>
<td>80%</td>
</tr>
<tr>
<td>2035</td>
<td>10%</td>
<td>21%</td>
<td>69%</td>
</tr>
</tbody>
</table>

RE = renewable energy, VRE = variable renewable energy.

**Figure 2: Rising Share of Variable Renewable Energy based Power in All Renewable Energy Applications**

<table>
<thead>
<tr>
<th>Year</th>
<th>VRE power</th>
<th>Other RE power</th>
<th>Other RE uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>2%</td>
<td>16%</td>
<td>82%</td>
</tr>
<tr>
<td>2030</td>
<td>15%</td>
<td>21%</td>
<td>64%</td>
</tr>
</tbody>
</table>

RE = renewable energy, VRE = variable renewable energy.
2. Prices are Trending Downward

8. As per IEA (2012), significant reduction in the capital cost of wind turbines and their improved performance had combined to reduce levelized cost of wind energy by a factor of three between 1980 and the early 2000s (to approximately 5 US cents per kWh by 2003). However, continued turbine up-scaling pushed up levelized costs of wind energy despite continued performance improvements to a level of 7.0–8.0 US cents/kWh by 2008. Levelized costs began to decline after 2008 and have continued to do so since then in line with long term trends.

9. Increases in conversion efficiencies of photovoltaic (PV) solar cells since the 1980s, and the resultant rise in PV module efficiencies, have contributed to increasing the cost competitiveness of PV technology. As per the United States Department of Energy (2011), module prices in 2010 were about 10% of that in the early 1980s. Simultaneously, rising production levels and reducing costs of balance-of-system (including storage batteries) have helped improve the viability of PV systems in increasing number of applications.

10. The levelized costs of wind and PV installations in 2015 indicate that both technologies can be considered competitive with conventional power generation—at least in locations with good wind regimes and solar irradiance levels.\(^4\)

11. Plunging PV module costs since the mid-2000s have somewhat diverted attention from concentrated solar power (CSP) technologies, although its inbuilt energy storage capability that reduces its variability would likely lead to its comeback.\(^5\)

3. The Need for Grid Management Services as VRE Penetration Increases

12. The variability of VRE output depends entirely on resource availability (solar-irradiance and wind-speed). Figures 3 illustrates the rapid changes in PV output due to changes in solar irradiance that can occur on a cloudy day, compared to a clear day. Figure 4 shows the extent wind power output at a given location can vary by time-of-day because of wind speed variations on any given day, as well as power output variations from one day to another. Figure 4 also shows a wind rose for a particular location, which depicts the percentage of time wind blows from a certain direction and in a certain speed range at that location.

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4 As per power purchase agreements with levelized costs of 3.0 US cents per kilowatt hour (cents /kWh) for onshore wind energy and 4.5 cents per kWh for solar photovoltaic (SPV) systems. Refer to http://bv.com/Home/news/solutions/energy/solar-wind-grid-parity

5 Refer to: http://www.solarpowerworldonline.com/2014/06/2014-trends-concentrated-solar-power/
Figure 3: Variability of Photovoltaic Output

Sunny Day

Cloudy Day


Figure 4: Variations in Windpower Output

Hourly Variations on Consecutive Days

13. Significant progress has been made in the past two decades in improving performance and efficiency, and reducing costs of VREs. However, the non-dispatchable nature of solar and wind energy has posed a challenge in grid stability, as the intermittent nature of solar insolation and wind speeds results in energy generation that is significantly more variable than the rates at which power demand and output from other types of generation plants change. IEA (2017) describes four phases of VRE penetration as per its impact on power system operations. These are phase 1 (up to around 3%), phase 2 (from 3% to 15%), Phase 3 (15% to 25%) and Phase 4 (25% to 50%). This paper considers that the IEA definition is not appropriate in the context of ADB client countries, which mostly have weak power systems, and a penetration of 3% can also have significant consequences for grid stability and power system operations.

14. In the context of ADB client countries, it is more appropriate to consider that VRE accounts for a small share if the resulting variation in the net power demand (total power demand less demand met by VRE) can be considered largely a perturbation—that is, where the resulting changes in frequency and voltage remain within stipulated limits. Beyond that, it can be considered a large share. There can also be “hotspots” because of transmission congestion, which can lead to VRE curtailment.

15. At higher penetrations, the variability of net power demand (a direct consequence of high share of VRE) can cause serious imbalances between power demand and supply, raise new challenges for system grid planning and operations, and can call for a system-wide transformative approach to increase flexibility of the power system. These can include the following: (i) grid infrastructure (including connections to other systems); (ii) demand response; (iii) energy storage; (iv) generation flexibility; and (v) policy and regulatory frameworks. Useful research findings that can facilitate VRE integration can be expected to emanate from “Mission Innovation” announced in November 2015.6

4. Commitments of ADB Client Countries on Decarbonization

16. In the Asia and Pacific context—as elsewhere—decarbonization will need to be accomplished by: (i) sustaining economic growth and uplifting the poor, the vast majority of which are in the Asia and the Pacific region; (ii) providing access to modern energy to all, including those in small island developing states (SIDS) and remote locations of other developing countries; and (iii) improving energy security at the national and subnational levels, including remote and isolated locations in SIDS and other countries.

17. More than 185 countries, including many developing and emerging economies that are ADB client countries, have pledged efforts to reduce GHG and CO₂ emissions through the intended nationally determined contributions (INDCs) submitted to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat. Subsequently, many INDCs have been reaffirmed as nationally determined contributions (NDCs).7

18. The INDCs/NDCs are an important component of the Paris Agreement adopted at the 21st Conference of Parties (COP21) that aims to achieve the long-term goal of limiting mean global temperature rise.8 The Paris Agreement, which entered into force in October 2016, offers direction in terms of (i) continuing efforts to keep temperature rises well below 2°C and pursue efforts to keep them below 1.5°C; (ii) returning regularly to review progress and (if necessary) strengthening climate action;

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6 Leaders of 20 countries and the European Union announced their plans to accelerate global energy innovation by doubling expenditure on clean energy research and development by 2020. For further details, refer to: http://mission-innovation.net/baseline-and-doubling-plans/

7 http://unfccc.int/focus/ndc_registry/items/9433.php

8 The INDCs/NDCs typically cover some or all of the following types of mitigation priorities: (i) Energy Sector: rising share of renewable energy and clean fuel/technology based power; (ii) Buildings: Energy efficient building designs, construction and retrofits; energy efficient appliances and equipment; and distributed generation options; (iii) Industry: Energy efficient equipment and processes, replace fossil fuels by chemical equivalents, distributed generation; (iv) Transport: electricity based cars, railways and urban mass transit systems; and (v) Agriculture, forestry, and land-use management to maximize carbon sequestration.
(iii) increasing transparency to ensure that climate action does take place; and (iv) finance, technology,
and capacity building to enable real change.

19. Least developed countries and SIDS are required to prepare and communicate to the UNFCCC
secretariat their strategies, plans, and actions for low GHG emissions development reflecting their special
circumstances. Over a period of time, the NDCs are to become increasingly ambitious and move closer to
achieving the long-term goal.

20. The mitigation activities covered by INDCs/NDCs of many countries indicate broad objectives of
increasing the penetration of renewable energy, and some provide specific targets too. A new NDC
Partnership launched at COP22 in November 2016, provides a platform to assist countries transform
these targets into specific strategies and measures, and to accelerate their climate commitments into
action.

B. The Significance for ADB

21. ADB energy sector interventions in its client countries are based on its Energy Policy of 2009. The
policy is aimed at providing reliable, adequate, and affordable energy supplies for growth in a socially,
economically and environmentally sustainable manner. It emphasizes: (i) promoting renewable energy
development and energy efficiency; (ii) expanding energy access; and (iii) building capacity, promoting
good governance, and supporting power sector reforms. With increasing emphasis on climate change
mitigation, ADB has increasingly supported clean energy development.

22. Since 2011, ADB has approved more than $2 billion annually in clean energy investments (Figure
5). In 2015, approvals for clean energy investments reached $2.5 billion and were almost 50% of the
total energy sector approvals during the year. In 2015, energy sector investment approvals themselves
reached a record $5.6 billion, which was about one third of the ADB’s total approvals of $16.5 billion.

23. Relating to ADB’s engagement in power generation, the energy policy continues to maintain
non-involvement in financing nuclear power generation. The policy is open for ADB’s assistance in the
development all other generation facilities, including conventional thermal and hydropower plants to the
extent that they fit in to the broad framework of clean energy development and increasing energy access
in line with the demands from ADB client countries. When such conventional power plant developments
are an integral part of the plan for increased renewable energy penetration in national grids, they can be
adequately justified within the policy. ADB interventions in conventional thermal power generation are
expected when the client country has committed to gradually increasing share of renewable energy in
the power generation mix, and taking other actions such as reducing fossil fuel subsidies and retiring old inefficient thermal power plants.

24. About 60% of these clean energy investments in ADB was in transmission and distribution either for supply side loss reduction or for evacuation of power from renewable energy sources. The remaining 40% largely included direct investments in renewable energy power plants such as medium and small hydropower, wind, solar thermal, and PV. These were either centralized or decentralized grid connected power plants or small off-grid systems serving the basic energy requirements of remote communities and sometimes providing income generating opportunities.

25. In developed countries where solar and/or wind energy technologies have penetrated beyond the 10% market share level on an annual basis, grid integration issues have come to the fore. In some countries of the Asia and the Pacific region, such grid integration problems have been experienced at significantly lower levels of penetration with VRE hotspots and transmission congestion in certain parts of the grid system. It is anticipated that these problems will be experienced in some more ADB client countries in the coming years as VRE penetration levels increase.

26. With the new targets set by ADB in 2015 for climate financing to increase from the present $3 billion a year to $6 billion by 2020, clean energy investments will have a significant share. Additionally, it is expected that by 2020, the contribution to climate financing by the energy sector alone will also need to increase, to be in line with cofinancing targets spelt out in ADB (2014a). In order to achieve these levels of support, ADB would need to explore all avenues to further increase its clean energy investments.

C. Paper’s Limitations

27. The paper is a high-level assessment of grid integration options—many of which are beginning to become relevant in some ADB client countries. It recognizes that significant power market reforms would be required for increasing VRE penetration, but does not dwell on the country-specific issues and constraints to power market reforms. The paper does not perform system-wide simulations, but relies on data, information, and results that are publicly available from credible sources.

28. Although capital costs of many VRE and grid integration technologies have reduced and their performance improved significantly over the past 5–10 years or more, the paper does not track any such past trends or project these trends forward. It provides a snapshot of scale and cost of various technology options that are presently mature, commercially viable, or improving rapidly to commercial viability, or where some field demonstrations have taken place. Technologies in the conceptual stage or where laboratory scale or a few pilot tests have been performed are not considered.

29. While it is recognized that financial resource availability would influence the deployment of VRE in many developing countries of Asia and the Pacific, the paper does not dwell on the issue of availability of climate finance from dedicated climate funds or elsewhere.

D. Paper’s Layout

30. Chapter II briefly refers to the outlook for VRE in the Asia and the Pacific region and ADB supported interventions with VRE integration component. Chapter III focuses on approaches adopted worldwide to increasing the absorption of VRE output in to power systems (i.e., towards facilitating grid

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9 However, with efforts to address grid integration issues, some developed countries have managed high levels of VRE penetration (mostly wind) on an annual basis in 2015, such as 42% in Denmark, 24% in Ireland, and 23% in Spain. Instantaneous VRE generation at times exceeded 100% of energy requirements in Spain.

10 These targets do not include cofinancing from external sources of climate finance and/or other sources of official and commercial cofinancing.
integration). Chapter IV builds on the findings from relevant experience world-wide and provides suggestions for ADB going forward.

II. VARIABLE RENEWABLE ENERGY IN ASIA AND THE PACIFIC

31. It is useful to distinguish between small and large power systems particularly when VRE generation shares are significant and on the rise, as small power systems offer relatively fewer options compared to large power systems for maintaining smooth operations. Small power systems refer to mini grids or microgrids in SIDS or isolated small grids in other countries that are powered essentially by diesel generators, and mini- or micro-hydro plants and other renewables. Large power systems refer to grid systems that can have a range of system characteristics in terms of generation technology and fuel types, transmission and distribution assets, and interconnections with other power systems. Table 1 shows the key differences between small and large power systems.

Table 1: Key Differences between Small and Large Power Systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Small Power System</th>
<th>Large Power System</th>
</tr>
</thead>
</table>
| VRE resource variability | - Small geographical area  
- Significantly different variability of solar and wind resource unlikely across the geography  
- Solar and wind may complement to reduce overall variability | - Large geographical area  
- Significantly different Variability of solar and wind resources likely across the geography  
- Solar (wind) variability at one location can complement solar (wind) variability at another location to reduce overall variability  
- Solar (wind) variability at any one location can complement wind (solar) variability at the same location |
| Power system inter-connection | - No interconnection with other power systems | - Can be interconnected within a country or across countries  
- Electricity import/export options can absorb some variability in VRE generation |
| Power storage      | - Only battery storage options                                                      | - Many power storage systems possible  
- Include battery, large conventional and pumped storage hydropower |
| Generation flexibility | - Determined often largely/only by cycling capability of diesel generators | - Determined often by cycling capabilities of a mix of steam thermal, gas turbine, diesel generators |

VRE = variable renewable energy.  

32. Although large power systems are more varied than small power systems, each system is unique. Given the variability and intermittence of generation from VRE, the implications of adding one unit of VRE capacity in a small power system is likely to be higher than in a large power system.

A. Variable Renewable Energy Penetration will increase in ADB Client Countries

33. All ADB client countries have submitted INDCs and outlined their commitments for reducing carbon emissions; most have reaffirmed their commitments in the NDC registry. Few INDCs/NDCs state absolute GHG emission reduction targets; most INDCs/NDCs provide targeted emission reduction from a projected business-as-usual scenario, or emission intensity reductions or reductions in per-capita

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11 In this paper, mini grids and microgrids are generically referred to as mini grids.
emissions. The INDCs/NDCs of many SIDS explicitly mention targets for VRE and other renewables. It is expected that VRE penetrations will be increasing in most, if not all ADB client countries in the foreseeable future.

34. Even though VRE penetration levels remain low to date in most cases, some countries have begun to pay attention to some aspects of integrating VRE into existing grids. For example, the People’s Republic of China (PRC) and India, where VRE accounts for 2%–3% of overall electricity generation, the concentration of VRE in certain parts is considerably high and has begun to highlight the need for new approaches to better absorb intermittent electricity generation from VRE. Similarly, VRE curtailment in some SIDS has prompted them to pay attention to VRE grid integration issues.

B. ADB Support for Grid Integration of Variable Renewable Energy

35. Although the grid integration objective has gained ground in recent years, most projects are still in their early stages and provide few firm lessons to date.

1. Grid Integration Challenges in Small Power Systems

36. While imported oil-based generation accounts for more than 90% of power generation in some SIDS, other SIDS have been using locally available renewable resources for power generation and have a significantly lower share of imported oil-based power generation. As per United Nations International Development Organization and International Center on Small Hydropower (2013), ADB (2015a) and the INDCs/NDCs submitted by various SIDS, the latter group includes Fiji, Papua New Guinea, Samoa, and Vanuatu.

37. A roadmap (IRENA, 2013a) developed for enhancing energy security through development of VRE and other renewable resources in Pacific SIDS shows the following:

(i) an integrated approach is required to promote energy efficiency in addition to VRE and other renewables;

(ii) large-scale penetration of VRE requires that the energy, water, and land-use nexus is comprehensively addressed upfront in consultation with all stakeholders (regional organizations, national and local government bodies, power utilities) to ensure social acceptance and leadership;

(iii) although VRE and other renewable resources would be the most sustainable and cost-effective solutions for the medium-term, hybrid solutions (such as a combination of diesel and VRE) can play a key role in the near term;

(iv) grid stability aspects need to be addressed for different levels of penetration of VRE and other renewables, for which grid performance needs to be modeled; and

(v) capacity development programs are required at various levels—from vocational education to training for policy makers and planners. These findings are relevant to Maldives, a SIDS outside the Pacific region.

38. In recent years, energy storage has been routinely considered in grid-connected VRE projects in SIDS. For example, ADB is supporting the installation of PV-diesel hybrid systems in about 160 inhabited islands of Maldives. Initially, PV-diesel hybrid systems—with relatively environmentally benign lithium-ion batteries—were designed for five islands, with the objective of minimizing levelized operating costs

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12 Many INDCs present two sets of targets that broadly reflect (i) unconditional pledges that they can achieve with their own resources; and (ii) pledges that are conditional upon financial, technical and other support from the global community.
(rather than maximizing the share of PV generation). A key concern is the disposal of spent batteries, although given the 10 years or higher battery life, it is possible that a viable approach can be found in time.

39. Another interesting project is for grid-connected PV systems in six southern islands of Cook Islands. Given that similar systems were set up previously in the northern islands of Cook Islands with New Zealand support, ADB has sought to adopt the same technical standards—an approach that recognizes the capacity limitations in the country. Although the standards were not restrictive and allowed for lead-acid batteries, upon accounting for environmental costs, SPV with lithium-ion batteries were assessed the least cost option.

2. Grid Integration Challenges in Large Power Systems

40. ADB supported projects seek to address grid integration issues of VREs in a few countries, the most prominent ones being the PRC, India and Sri Lanka.

41. In the PRC, ADB support includes both TA and investment projects. Two TA projects made policy recommendations: one to modify the traditional generation scheduling and dispatch system to prioritize offtake of VRE and other renewable energy, and the other to require large SPV facilities to be equipped with the fault-ride-through function to ensure grid stability and safety. ADB has also supported the introduction of smart grid technologies to enable VRE output from resource-rich northern provinces to be delivered to demand centers in eastern PRC. Although the PRC is committed to reducing VRE curtailment, Parkinson (2016) notes that it is likely that wind power is still curtailed as wind power capacity grew rapidly without a commensurate increase in grid capacity.

42. Another TA project helped prepare a roadmap for concentrated solar power (CSP), one of its outputs being a technology assessment manual. It screened many potential CSP demonstration sites and catalyzed the introduction of CSP technology in the PRC by supporting a pre-feasibility study. ADB also supported a pioneering CSP project, which incorporates a complex new technology with significant storage capacity.

43. In India, ADB continues to support transmission grid strengthening and grid extension to connect VRE capacity. ADB also supported a road map for smart grids with a view to managing VRE curtailment. It recommended short and medium-term actions to enable smooth power system operations in a power system with large VRE share. Some recommended activities, such as VRE resource forecasting and control systems, are being supported by other development partners.

44. In northern Sri Lanka, where large VRE capacity additions are planned and grid integration aspects have begun to emerge, ADB is facilitating the development of a 375 MW wind park. The Japan International Cooperation Agency has investigated the feasibility of various electricity storage options, including batteries and pumped hydropower.

45. ADB has supported among the first utility size grid-connected VRE capacity in Bangladesh and Uzbekistan. Given the low VRE penetration in Bangladesh and Uzbekistan (less than a fraction of a percentage point) no significant VRE grid integration issues have arisen so far.

46. ADB has supported several nonsovereign/private sector VRE investments in several countries, notably India and Thailand. Available information on these projects indicates that these projects aim to demonstrate a certain VRE technology or a new business model or catalyzing the private sector, but does not provide any indication on whether they address grid integration issues.
III. OVERVIEW OF GRID INTEGRATION OPTIONS WORLDWIDE

47. Among the important preconditions for continued development of grid-connected VRE facilities are: (i) that VRE facilities are given quick and reliable open access to the grid (or mini grid); and (ii) the grid (or mini grid) can balance electricity supply and demand at all times while VRE output continues to vary. Financial concerns impinge upon both preconditions.

48. A series of finance related problems can arise for a simple interconnection of a VRE facility with a power system. At high levels of VRE penetration, additional costs come into play. These relate to load balancing and maintaining system stability, and include but are not limited to incremental costs of (i) operating and maintaining dispatchable power generators, power storage systems, and smart grids; and (ii) designing and managing programs or systems that encourage customers to time-shift loads (demand response) to facilitate load balancing. In some cases, fuel cost savings from increased VRE output can be significant, and may even exceed incremental costs. Appropriate regulations need to be in place and complied with.

A. Policy and Regulatory Framework

49. To date, most policy makers and power sector stakeholders in the Asia and Pacific region have focused largely on facilitating investment in VRE facilities, grid interconnection, and the associated capacity building. The most prominent policy measures in both small and large power systems have related to favorable feed-in-tariffs for and priority off-take of VRE output by the power utility. This suffices for low levels of VRE penetration, where the VRE component of overall generation is small, and most entities connected to the grid either only generate or only consume electricity. For higher levels of penetration, a new policy framework is required to encourage investment and operating practices that optimize power system performance (in terms of cost, reliability, GHG emissions).

1. Finding New Business Models to VRE Investment at Low Penetration Levels

50. In both small and large power systems, VRE output can be considered as having a low share if (i) the power utility can view intermittent VRE generation as causing perturbations to electricity it is required to transmit and distribute; (ii) VRE output does not upset grid stability and reliability, i.e., the quality of power supply is not noticeably adversely affected; and (iii) the power utility’s financial situation is not significantly affected by VRE power off-takes, i.e., even when feed-in-tariffs are attractive to VRE developers, the average generation cost of electricity flowing into the power system does not increase significantly. In other words, end-user tariffs, utility finances and government subsidy obligations are not materially affected at low levels of VRE penetration.

51. At low levels of VRE penetration, the major policy concern normally is to provide the following: (i) adequate incentive for investment in VRE projects, which is mostly through a favorable feed-in-tariff; and (ii) a power market that provides non-utility owned and operated VRE facilities non-discriminatory access to the grid, i.e., the sector policy allows electricity off-take from VRE facilities, whether publicly owned or private. Where net metering is done, it makes it easy for a utility to settle accounts for its power purchase from and sales to a particular entity that sets up a VRE facility. There can be preferential access for VRE, i.e., the grid is obliged to off-take VRE generated electricity. The trick is to find business models where utilities can profit from, and even encourage VRE.

13 Some examples include Germany and Mexico.
2. Promoting Flexible Power Market Structure to Support High VRE Penetration

52. At high penetration levels, the power grid system cannot easily accommodate rapid changes in VRE output, and a combination of the following actions is required to maintain system integrity and offer affordable VRE to consumers: (i) regulating system frequency and voltage so that they remain within stipulated limits; (ii) carrying out utility scale load following, i.e., adjusting generation in meeting power demand at any given time; (iii) time-shifting loads during a 24-hour day, i.e., adjusting demand levels to avoid mismatch between power demand and supply; and (iv) modulating seasonal variations by storing energy during months or seasons when (with the naturally available renewable resources) energy generation exceeds demand, and discharging energy during months or seasons when renewable energy resources are scarce.

53. Policies that promote a flexible power market structure and provide for balancing of power supply with demand are most important for facilitating a high level of VRE penetration. Although these policy measures are discussed in the context of large power systems, many can also be applied to small power systems.

54. **Power market structure.** Having power purchase agreements with conventional base-load and peaking generators is convenient for grid operators—but such power purchase agreements (often with take-or-pay clauses) reduce the flexibility of the electricity network. They lead to curtailment of VRE output. A more flexible allocation of power generation can enhance the ability of the power system to accommodate high shares of VRE. Efforts to unbundle the power systems and establish a wholesale power market have progressed in some countries in developing Asia, such as India and the Philippines.

55. Where retail power markets—that allow electricity consumers to freely choose their electricity suppliers—are envisaged, it is likely the demand responsiveness to supply prices will increase significantly, which can benefit VRE generators.

56. The downside of liberalized power markets is that utilities no longer have the ability to plan for how they will meet demand. Integrated resource planning (if done well) can enable utilities to better match VRE and other renewable resources to demand and address some of the integration challenges affordably.

57. **Balancing power supply and demand.** Even in the best of circumstances, grid operators can experience temporary imbalances as a power plant or transmission line unexpectedly goes out of service or power demand unexpectedly surges or dips. With increasing VRE penetration, such imbalances increase and the power system needs to adjust to frequent changes in VRE output (daily and seasonal peaks and troughs)—which can range from zero or nearly zero to a significant share of power demand during a 24-hour cycle. Ancillary services for system security therefore become an important aspect of supply and demand balancing.\(^\text{14}\)

58. Many approaches to balance power supply and demand at all times can be driven by policy (along with investment and capacity development). These technical and management approaches are required more so as the share of VRE increases, and include the following: (a) enabling system generation to follow the load; (ii) changing demand levels in response to power supply variability; (iii) building electricity storage capacity in the power system; and (iv) establishing smart grids with digital communication between all players. The relative importance of any specific approach depends on the specific characteristics of the existing power system.

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\(^{14}\) Ancillary services include (among others) black start capability to enable grid restart following a black-out, frequency regulation to maintain system frequency with automatic and quick responses, spinning reserve to provide additional energy when needed, and reactive power compensation.
59. Other policy measures. Standards for VRE and grid interconnection can reduce risk of failure and provide comfort to VRE investors. Environmental standards would apply to VRE facilities and other measures for grid integration (such as storage batteries). Other policy measures may become important over a period of time, for instance, regulations that guarantee access to sunlight after SPV panels have been installed on building walls.

B. Technical Options for Small Power Systems

60. Each mini grid—whether in an isolated area in a large country or in some island in a SIDS—is unique in terms of its VRE and other renewable resource base, existing generation and distribution infrastructure, customer mix, load profile, and other characteristics that include policies and regulations, organizational structures, skill base and other factors. Integrating large amounts of intermittent VRE resources on isolated diesel-based mini grids poses significant technical challenges. Location-specific and community-specific project sustainability strategies would be required for long-term success of VRE investments. There is no typical optimal hybrid technology mix.

61. Observations from examples of high VRE penetration in small power systems in SIDS and other countries provide useful lessons for advancing VRE in other small power systems.

62. Small island developing states. The size of mini grids (in terms of total load and generating capacity typically found in SIDS) limits grid integration and energy storage options in the foreseeable future mostly to batteries. It is therefore highly likely that deployment of environmentally-friendly batteries and environmentally-friendly approaches to battery disposal will become important in the coming years.

63. The Tokelau archipelago, which comprises three atolls about 500 km north of Samoa,\(^\text{15}\) provides interesting insights into the design of high VRE penetration VRE–diesel hybrid systems in mini grids. As per the Government of Tokelau (2013) and IRENA (2013b), for PV systems to provide more than 90% of (high quality and reliable) power supply in Tokelau’s three islands the peak-watt capacity of the PV modules, string invertors and battery invertors should be at least twice as large as the peak system load. Additionally, with about 25% of the PV output stored in batteries, there is no need for diesel generators (that may include some that are old and inefficient) to provide reserve. In these three islands, the normal practice is to operate diesel plants at or near full capacity (i.e., at or near the highest fuel-efficiency levels when carbon emissions are at or near lowest levels) whenever diesel generation is required. Locally available biomass options can be considered (such as coconut oil in Tokelau) to further reduce oil imports and carbon emissions.

64. Isolated mini grids. Noteworthy observations by National Renewable Energy Laboratory (NREL) and Wlnrock International (2015) from a study of three mini grids in Indonesia\(^\text{16}\) include the following: (i) the most important determinants of VRE attractiveness are the upfront installation costs (which includes costs of energy storage and interconnection with the mini grid) and the capacity factor; (ii) VRE is generally not well positioned if alternative renewable resources are locally available—in other words, VRE is generally less attractive than the relatively more dispatchable renewables such as biogas or coconut oil or palm oil, for which relatively inexpensive feedstock storage amounts to low-cost electricity storage; and (iii) an energy storage system coupled with a VRE installation enhances the value of VRE generation—as energy storage provides some load balancing services. Therefore, if feed-in-tariff was to broadly reflect

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\(^{13}\) In each of three atolls (Atafu, Fakaofo and Nukunonu), there is a village on one island while the rest are uninhabited. The total resident population is about 1,400 distributed fairly evenly between the atolls.

\(^{16}\) The three mini grids are Lamandau District of Central Kalimantan along with Sabu and Sumba Islands of East Nusa Tenggara province in Indonesia. All three locations have high electricity generation costs, high poverty rates, diesel dependencies, relatively low electrification ratios, reasonable site access, excellent renewable energy potential, substantial load growth (10% to 20% annually), and broad support for development of VRE and other renewable resources from multiple stakeholders including the power utility, regional governments, and nongovernmental organizations.
the value of VRE, it would be higher when VRE was accompanied by some storage capacity—which is consistent with the fact that upfront investment increases when storage capacity is added.

C. Technical Options for Large Power Systems

1. Managing Conventional Generation Resources

65. Improved flexibility of non-VRE generators enables power systems to better follow demand movements and VRE generation variations, no matter what efforts are made to store electricity. The experience of some countries improving such capabilities of non-VRE generators provides interesting lessons for some Asian countries.

a. Generation Flexibility

66. Most thermal power plants cycle to a certain degree as they start, stop, and raise or lower power output. Increased VRE penetration increases the need for operational flexibility of the thermal power plants when they comprise a significant share of installed capacity. The need for increased flexibility is in terms of reduced minimum level of generation with a stable flame, faster start and stop, and faster ramp up and ramp down of power output. Although the impact of cycling on equipment performance is small when steam-thermal units provide base-load power, the impacts increase when cycling requirements increase significantly. Equipment undergoes thermal stresses even at low loads. Additionally, plant operators are not accustomed to running steam thermal units at low load.

67. Operating experience in the United States over more than a decade has demonstrated that some coal-fired power generation units in a power system can become flexible resources. For coal-fired units with horizontal boilers and automated drains, it is shown that increased flexibility requires limited hardware modifications but extensive modifications of operating practices (Box 1).
NREL et al (2013a) have simulated power system operations with increased flexibility of selected coal-fired steam units and shown benefits at the system level (i.e., overall reduction in fuel costs and emissions) coupled with reduced VRE curtailment. Additionally, low-load operations have increased for large sub-critical and super-critical plants.

Increased cycling leads to wear-and-tear and increased maintenance requirements. The impact from cycling can take several years to show up as damage or forced outages. Although compared to base-load operations, cycling damages plant equipment and impacts its useful life, changes in operating practices and training programs can minimize the adverse effects of cycling. Utilities have installed additional equipment and implemented new procedures to reduce the effects of cyclic operations, which may include: increased monitoring and inspections, improved control systems, systems to bypass steam to the condenser, boiler and turbine stress analyzers, and increased water treatment and analysis.

The horizontal boiler design facilitates cycling by improving the drainage which in turn reduces corrosion fatigue. In units that have pendant design boilers, water accumulates at the bottom and drainage is slow. In these units, although the basic boiler design cannot be modified, other hardware modifications can be considered.

For coal fired power plant units with horizontal boilers, approximately 90% of the plant’s subsequent savings came from changes to operating procedures after physical modifications are in place. Effective operating procedures require an understanding of all components impacted by cycling. For example, controlling temperature rise during unit start-up and temperature drop during unit shutdown required changes in plant operating procedures, such as increased temperature monitoring of boiler and turbine parts.

**Box 1: Making Coal-fired Power Plants Flexible**

In the United States, most coal-fired power plant units have not been started and stopped more often in any given calendar year between 2000 and 2011, while VRE (wind power) generation has increased more than 30-folds. Yet there is a reasonable sample of power plants that have 2–3 times more start-stop cycles per year. Additionally, low-load operations have increased for large sub-critical and super-critical plants.

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68. NREL et al (2013a) have simulated power system operations with increased flexibility of selected coal-fired steam units and shown benefits at the system level (i.e., overall reduction in fuel costs and emissions) coupled with reduced VRE curtailment. 17

69. NREL et al (2013b) show that unit level benefits (in terms of net revenue increases) can be achieved for coal-fired units with better maintenance and cycling retrofits, 18 while the remaining coal-fired units can operate with an overall reduction in cycling. 19 In general, although emission rates during cycling can be higher than during steady-state operation, CO2 emissions reduce system-wide because of avoided emissions from increased absorption or reduced curtailment of VRE output. Retrofits and improved maintenance practices for reducing minimum generating levels of coal-fired units are found to have the most beneficial impact on the system.

70. NREL et al (2013a) have also observed that the benefit of increasing operational flexibility of steam thermal plants need not always lead to a net benefit at the system level. In a gas-dominated system with many combined cycle power plants and less coal-fired capacity, efforts to retrofit coal plants for improved cycling does not provide benefit; in such a system, it is likely best that flexibility of gas-fired steam capacity be improved. And given the high inherent flexibility of gas turbines, increasing their flexibility in a coal dominated system does not provide significant benefits.

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17 The simulations are for a power system comprised of 45% coal fired capacity, 32% combined cycle capacity and 23% open-cycle gas turbine capacity.
18 Net revenue increases refer to incremental revenue less incremental operation and maintenance cost (including fuel cost, other variable operation and maintenance cost, start and shut-down cost).
19 Vis-à-vis a business-as-usual situation of no cycling improvement effort in any coal-fired unit.
b. Large Hydropower Plants with Storage Reservoirs

71. Hydrological flows have low short-term variability, although water flow variability over a longer (seasonal) time-scale is comparable to that of wind and solar. On a year-to-year basis, water flow variability can be even larger. Water storage can help smooth out natural water flows, enable hydropower plants to provide firm power, and make hydropower a good complement to VRE. Nonetheless, climate change can impact the benefits of water storage capacity, as frequency and intensity of droughts increases.

72. Although hydropower capacity was built to serve the specific water storage needs for generating electricity and other uses (for example, irrigation), it can be and has been used to facilitate the integration of VREs, especially wind. An example is the Norwegian hydropower system, where water storage capacity (84 terawatt-hours [TWh]) is equivalent to 8 months of average hydropower output (124 TWh). This storage capacity has been a useful backup for wind power. Without it, Denmark’s annual wind power share of more than 30% would not be possible. Figure 6 shows that natural water flows (which fill up reservoirs) are high in months when wind power generation is low, and vice-versa.

73. Owing to wind-speed variability on a day-to-day basis, Norway imports power from Denmark when wind speeds are high, and reduces drawdown of the hydro storage reservoirs. Conversely, Norway increases drawdown on hydro reservoirs when wind speeds are low and Denmark needs to import power. Such cycles are repeated on a daily basis (Figure 7) and lead to a reservoir management system with daily cycling. This is different from the traditional system of managing a reservoir.
74. From available information in the European experience, it appears that managing hydro storage to accommodate VREs can be without detriment to the original function of hydropower capacity, and results in a more productive use of capital investments already made.

75. The complementarity between hydro and wind can be exploited within national boundaries too. In Brazil, predominantly a hydropower based system, and where heightened environmental concerns regarding large hydropower projects (as elsewhere) makes construction more difficult increasing wind power capacity is seen as a clean way to meet electricity demand in the dry season as the wind regime is the strongest at the time.  

76. Given the complementarity between hydro and wind, it can be useful to expand hydro storage capacity in existing dams. Retrofits can enable reservoir operators to utilize a significant portion of the unused storage volume with little or no decrease in spillway capacity. Such retrofits would likely be useful as (the anticipated) climate change leads to increased flooding during the wet season and lower rainfall during the rest of the year. Successful examples of retrofits to increase hydro storage capacity include some in Brazil and Malawi. 

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20 https://revista.drclas.harvard.edu/book/power-brazilian-wind
21 França Dam in Brazil, constructed in 1996 for irrigation and drinking water supply for the populations of the semi-arid state of Bahia, offers a reservoir of high-quality water. After the major drought that began in 2012 (the worst in the last 50 years), the fusegates system was installed to increase the reservoir capacity by approximately 30%. Kamuzu Dams I and II were built in Malawi to respond to increasing water demands from the town of Lilongwe. For raising the normal water level of Kamuzu II by 5 m, the installation of concrete fusegates made it possible to more than double the reservoir storage capacity from 8.9 million m³ to 19.8 million m³. Further details are in: http://www.hydroplus.com/hydroplus/hydroplus. nsf/web/index.htm&lng=L2
77. For existing hydropower projects without retrofits, the incremental costs of integrating VRE appear to be low, and mainly for training of operators that requires them to modulate drawdown levels rather more frequently—with perhaps a daily cycle embedded in an annual cycle.

2. Improvements and Innovations in Energy Storage

78. Energy storage does not produce energy, but enables the optimization of energy delivery and use, and can significantly alter the energy market landscape. Almost all installed energy storage capacity across the globe is based on hydropower. In its estimates of global electricity storage capacity, the IEA (2014) did not consider storage associated with conventional hydropower. It estimated total installed pumped hydropower storage (PHS) capacity at some 140 GW in 2013, which was more than 99% of global electricity storage capacity. The Intergovernmental Panel on Climate change (2014) recognizes that conventional hydropower provides opportunity for energy and water storage, but notes that PHS is the only widely deployed energy storage technology.

a. Hydropower-based Storage

79. Conventional hydropower storage. Given the general tendency to ignore the energy storage capability of conventional hydropower plants, the cost data per unit of storage capacity of conventional hydropower plants is not recorded in publicly available data sources; capital cost data per unit of generating capacity is recorded. Experience in Northern Europe shows that a high VRE share intensifies the use of the reservoir. The reservoir is more effectively utilized with little additional cost other than operator training.

80. Pumped hydropower storage. Although PHS is the recognized front runner among electricity storage options, its prospects may be limited by environmental considerations, local resistance, and long lead-times. Nonetheless, increasing penetration of VRE can improve the outlook for new PHS capacity. According to Yang (2013), more than 100 new PHS plants with a combined capacity of 74 GW are expected to come into operation by 2020. Europe and USA are witnessing a revival of PHS as they push for more VRE. Japan is continuing to invest in PHS.

81. Traditional PHS plants with fixed-speed pump turbines typically have round-trip efficiencies of about 75%, and provide frequency regulation benefits only during the generation mode. Retrofitting of variable speed pump technology has helped improve round trip efficiency of existing PHS plants to up to 85% and enabled frequency modulation in both pumping and generating modes. Lefebvre et al (2015) note that numerous existing PHS facilities worldwide have been retrofitted to provide grid-balancing services in both modes. although, Henry et al (2013) noted that some constraints and limitations—from civil structures or hydraulic circuits—must be assessed before such retrofits can be made. Costs associated with PHS are site-specific. As estimated in the Sandia Report (2015), for an installed PHS capacity in the 300–1,300 MW range, the levelized cost is typically $150–$220 per megawatt-hour (MWh) and storage of around 8–16 kilowatt-hour per kilowatt (kWh/kW).

b. Other Storage Options

82. Various electricity storage options are emerging to help balance power demand and supply in all time-scales (from seconds and minutes to days and months) and with different size, charge-discharge, and cost characteristics.

83. Compressed air energy storage. Compressed Air Energy Storage (CAES) is the only storage technology that can compete with PHS in terms of storage capacity. The unit size is typically in the 100 MW range, discharge times can be several hours, it is normally operated with one daily storage and discharge cycle and has good load following capability. Compressed air can be stored either in underground caverns or steel above-ground storage reservoirs. Although proven commercially viable, the
CAES technology is not mature. After more than two decades when no new CAES plants were commissioned world-wide, new investment is appearing. Overton (2014) estimates that 11 GW of new capacity will be installed by 2023. As per the Pacific Northwest National Laboratories (2013), while there are many ideas to improve efficiency for air compression and reduce heat rates of gas turbine units, perhaps the most notable recent development is the possibility of CAES plants with much larger energy storage capacity per kW of about 480 kWh per kW, compared to less than 10 hours typical of PHS and most battery systems. If this kind of energy storage capacity is confirmed, some CAES plants will be able to respond to seasonal or month-to-month variations as well as to those over time-scales of a day or less—this will give CAES unique capabilities among the new storage technologies and may evoke special interest in terms of VRE integration.

84. **Flywheels.** Flywheels have been tried as storage devices. Their capacities tend to be smaller than PSH and CAES, but flywheels have rapid charge and discharge response. They have been operated with more than 5000 storage–discharge cycles annually and have proved to be durable in terms of number of cycles that can exceed 100,000. This makes them good for frequency and voltage regulation. Rastler (2010) documents the use of flywheels for frequency regulation and to integrate wind power in two Japanese utilities.

85. **Batteries.** Flywheels can compete with various batteries for frequency regulation. But batteries can also facilitate load following and time-shifting of loads. Existing types of batteries are improving and new types of batteries are appearing. This technological evolution is projected to lead to massive growth in the global market for utility-scale batteries by the early- to mid-2020s.

86. Lead-acid batteries, the oldest form of rechargeable battery technology, and the most commercially mature rechargeable battery technology in the world, is used in a variety of special applications, including automotive, marine, telecommunications, and uninterruptible power supply systems. However, there have been very few utility grid support applications for such batteries due to their relatively heavy weight, large bulk, cycle-life limitations, and perceived reliability issues (stemming from maintenance requirements). Advanced lead-acid technology batteries are beginning to appear in utility markets. Hitachi is developing an advanced lead-acid battery for renewable integration and smart grid projects in Japan; it has integrated advanced batteries with wind-generation sites (for example, the Tappi Wind Park set up in 2001).

87. The lithium-ion battery is the most widely deployed type, due in part to the intense development of Li-ion for use in transport vehicles. Although the needs for transport—high energy density—are distinct from the power system needs—where durability is more important, the transport application has allowed refinement of the design of different types of Li-ion batteries and provided some economies of scale. The most striking example is the Tesla initiative, which is part of a broader move to distributed storage located at the premises of residential and commercial consumers, who will usually be a distributed solar power generator.

88. **Thermal storage.** Thermal storage in buildings can reduce power demand (increase energy efficiency) or time-shift power demand. CSP installations normally incorporate thermal storage to facilitate load following and time shifting. This improves CSP positioning vis-à-vis PV and wind technologies.

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22 Two plants, with a combined storage capacity of 400 MW have been operating for more than two decades, but no new capacity has been added world-wide since 1991.
23 From $164.0 million in 2014 (a tiny base) to more than $2.5 billion by 2023. See Overton (2014).
24 Thermal storage technologies refer to storage of hot or cold fluids or phase change materials that provide cooling for buildings or electricity generation.
c. Comparison of Storage Options for a range of Grid Management Services

89. Electricity storage technologies can be positioned according to their power and energy characteristic and can provide a range of grid management services that include frequency regulation, load following and time-shifting of loads. Innovations in energy storage have reduced cost and improved cycle efficiency over a broad range of (i) capacities, from the kilowatt to thousands of gigawatt levels; and (ii) applications that range from frequency modulation to bulk power management. Innovations in reducing discharge times (that may range from seconds to several hours) for different types of storage have improved load balancing.

90. CAES and PHS can discharge in tens of hours and have capacities that can reach several hundred MW. In comparison, various electrochemical batteries and flywheels have low power and shorter discharge times that range from a few seconds to a few hours. 25

91. Both hydropower and CAES can have siting limitations. The environmental concerns for conventional hydro and PHS are generally well recognized. Siting of underground CAES storage systems involves finding suitable sites and verifying their air storage integrity. Such sites can be difficult to find. Above ground CAES can be less susceptible to siting limitations.

92. Table 2 provides a snapshot of levelized cost of these technologies which reflect trends in deployment, performance, and design features. The levelized cost of storage reflects the following aspects: (i) typical size range; (ii) storage capacity (kWh per kW); (iii) capital cost in $ per kW; (iv) number of storage-discharge cycles per year; (v) capacity factor; (vi) round trip efficiency of a charge-discharge cycle; 26 and (vii) status of maturity and commercial viability.

Table 2: Key Characteristics of Storage Options

<table>
<thead>
<tr>
<th>Storage Option</th>
<th>Storage Application</th>
<th>Status</th>
<th>Levelized Cost ($/MWh)</th>
<th>Typical Size (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped Storage Hydro</td>
<td>FR, LF, TS</td>
<td>Mature</td>
<td>150–220</td>
<td>280–1,300</td>
</tr>
<tr>
<td>Compressed air storage (underground)</td>
<td>LF, TS</td>
<td>Commercial/utility scale</td>
<td>120</td>
<td>136–408</td>
</tr>
<tr>
<td>Compressed air storage (above ground)</td>
<td>LF, TS</td>
<td>Experimental</td>
<td>210</td>
<td>50</td>
</tr>
<tr>
<td>Flywheel</td>
<td>FR</td>
<td>New commercial</td>
<td>380</td>
<td>25</td>
</tr>
<tr>
<td>CSP Thermal Storage</td>
<td>LF, TS</td>
<td>New commercial</td>
<td>170–290</td>
<td></td>
</tr>
<tr>
<td>Advanced Lead acid (utility scale)</td>
<td>FR, LF, TS</td>
<td>Mature–improving</td>
<td>130–225</td>
<td>1–12</td>
</tr>
<tr>
<td>Advanced Lead acid (distributed storage)</td>
<td>FR, LF, TS</td>
<td>New commercial</td>
<td>300–1700</td>
<td>0.025–0.05</td>
</tr>
<tr>
<td>Lithium-Ion (utility scale)</td>
<td>FR, LF, TS</td>
<td>New commercial</td>
<td>90–350</td>
<td>1–10</td>
</tr>
<tr>
<td>Lithium-ion (distributed storage)</td>
<td>FR, LF, TS</td>
<td>New commercial</td>
<td>260–1,260</td>
<td>1–10</td>
</tr>
<tr>
<td>Sodium sulfur (utility scale)</td>
<td>LF, TS</td>
<td>Signifcat recent commercial experience</td>
<td>260–295</td>
<td>1–100</td>
</tr>
<tr>
<td>Sodium metal halide (utility scale)</td>
<td>Integrate RE</td>
<td>Limited field demonstration</td>
<td>300–650</td>
<td>1–50</td>
</tr>
<tr>
<td>Vanadium Redox (utility scale)</td>
<td>Integrate RE</td>
<td>Limited field demonstration</td>
<td>430–560</td>
<td>1–50</td>
</tr>
</tbody>
</table>

25 Sodium sulfur battery systems and potentially certain flow battery systems discharge times can be as high as 6 hours.

26 AC to AC basis for utility applications (frequency regulation, load following, load modulation) and DC to DC basis for distributed storage.
<table>
<thead>
<tr>
<th>Storage Option</th>
<th>Storage Application</th>
<th>Status</th>
<th>Levelized Cost ($/MWh)</th>
<th>Typical Size (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vanadium Redox (distributed storage)</td>
<td>Integrate RE</td>
<td>Limited field</td>
<td>800</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>demonstration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc bromine (utility scale)</td>
<td>Integrate RE</td>
<td>Early stage demonstration trials</td>
<td>200–900</td>
<td>1–50</td>
</tr>
<tr>
<td>Iron chromium (utility scale)</td>
<td>Integrate RE</td>
<td>Experimental</td>
<td>150–250</td>
<td>1–100</td>
</tr>
</tbody>
</table>

FR = frequency regulation, LF = load following, RE = renewable energy, TS = time-shifting of load.


93. Table 2 shows that some storage technologies are mature and commercially viable. In particular, advanced lead-acid batteries and lithium-ion batteries can already compete with PHS and CAES in terms of cost—although not in terms of size. However, other battery types are at various stages of pre-commercial development at the laboratory scale, small pilots, or demonstration trials. Their costs are still significantly higher than PHS and CAES, although some are beginning to approach competitive cost levels for niche applications. 27 Other emerging storage technologies could also change the competitive landscape of storage technologies in the foreseeable future. It is useful to track improvements in battery technology and cost reductions. Whether reduced battery costs will enable utilities with high VRE penetration to simply do away with the hydro/CAES sized storage capacity requirements appears highly unlikely.

3. Demand Response Approaches

94. In this paper, demand response refers to a behind-the-meter consumer-side function of reducing consumers’ electricity demand during hours (time of day) when supply is tight and shifting to a time when supply is more abundant. 28 Demand response is implemented with the help of systems to control when particular loads (equipment or appliances) can or should be connected and switched on. 29 The demand response approach is distinct from demand-side energy efficiency which refers to a reduction in the consumption of energy required to perform a particular economic activity. 30

95. Traditionally, demand response approaches have helped moderate consumer demand at times of exceptionally high peaks (such as on a hot summer day) and to manage grid supply-side emergency events (such as outage of power plants or transmission lines). Godin (2013) and Smart Energy Demand Coalition (2014) describe demand response programs that have been implemented in the United States and Europe, where power supply reliability is high, and consumers are accustomed to high quality power. In these programs, the calls on demand response capability have been rather infrequent and the programs have entailed high cost (Box 2).

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27 Most notably, for niche applications in telecommunications, iron-chromium batteries appear to be cost competitive.
28 Demand response is sometimes defined to also include other behind-the-meter electricity functions such as distributed storage and distributed generation. Distribution storage incorporates use of various types of batteries. Distributed generation can include VRE (for example, photovoltaic), cogeneration and emergency (back-up) generation.
29 This includes smart equipment and appliances that can communicate and be controlled through the internet.
30 Demand-side energy efficiency requires inherently energy efficient equipment or appliances that have the same output (i.e., perform the same activity) but with lesser energy input.
Smart Energy Demand Coalition (2014) considers demand response as a cost-effective GHG-free balancing resource for VRE. High VRE penetrations will likely require that demand response capabilities are invoked more frequently, which will reduce the cost of demand response on a per megawatt-hour basis.

Pricing mechanisms can help time-shift some load. In addition to time-of-use pricing that has been tried and implemented across the globe since the 1980s, real-time pricing and critical-peak pricing systems have become possible with smart metering and other smart grid technologies.

4. Grid Flexibility

Power utilities have dealt with demand variations for several decades. The demand profile in a power system, which depends on the customer mix and customer load profile, varies from place to place and is strongly influenced by the time-zone and latitude. This explains the fact that the overall national peak electricity demand in a large country is less than the sum of provincial peaks. The consequent reduced need for reserve capacity and spinning reserve has traditionally provided the rationale for integrating transmission grids within a country. Similar benefits can come from integration of power grids across international boundaries.

The intermittence of wind speed and solar energy resource at a particular place—and differences in wind and solar energy resource across locations at a particular time—reinforces the need for integrating grid operations across power systems. The combined integrated power system can absorb more VRE output than the sum total of VRE outputs that the individual original (prior to integration) power systems can off-take.

If power systems cover a small geographical area, then it becomes useful to consider integrating two or more adjacent power systems within a country, or across international boundaries. Within national boundaries, it is very likely the regulatory frameworks will be similar across the various power systems. However, when integrating power systems across international boundaries, their regulatory frameworks may need to be carefully examined and harmonized.

5. Smart Grid

Smart grids can help to better manage variability on the supply side (which will increase with rising VRE penetrations) as well as the demand side, and help track cost of VRE integration. ADB’s Smart Grid Task Force (SGTF), has suggested approaches for supporting adoption of smart grid technologies in ADB operations (ADB, 2015b). Among other aspects, the SGTF addressed the issue of increased

<table>
<thead>
<tr>
<th>Box 2: Cost-Effectiveness of Demand Response Programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>The actual number of hours in a year when super-peaks occur and grid emergencies need to be managed can be low in advanced countries (less than 100 hours per year). Therefore, the demand response program cost on a per megawatt-hour basis can be quite high in these countries.</td>
</tr>
<tr>
<td>A review of the cost effectiveness of demand response programs in the United States shows that:</td>
</tr>
<tr>
<td>(i) cost of capacity contracted for demand response is below $50 per kilowatt per year; and</td>
</tr>
<tr>
<td>(ii) as actual load shifting is normally significantly less than that contracted for shifting, the actual cost of demand response can be considerably higher, at about $100 per kilowatt per year.</td>
</tr>
<tr>
<td>This cost level is justified as the cost of marginal supply capacity for meeting super-peaks and managing grid emergencies is still higher.</td>
</tr>
</tbody>
</table>

31 It is likely that higher latitudes will be colder than lower latitudes.
absorption of renewable energy, and focused on (among other components) weather forecasting, distribution generation monitoring and deployment of energy storage.

102. This paper recognizes that with data management, control technologies and communication systems, smart grids improve the operational efficiency and flexibility of a power system. Some aspects of smart grids are shown in Box 3. By improving the ability to stabilize grid operations through better frequency regulation, load following and time-shifting of loads, plus better managing off-take from distributed generation sources, smart grids can facilitate increased VRE penetration. Reliable VRE resource and output forecasts can also contribute to enhancing absorption of VRE output.

<table>
<thead>
<tr>
<th>Box 3: Functionality and Benefits of Smart Grids</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Improve energy accounting (through advanced metering infrastructure).</td>
</tr>
<tr>
<td>(ii) Reduce voltage drop across long lines (through distribution automation technologies).</td>
</tr>
<tr>
<td>(iii) Reduce frequency and duration of outages (through automated fault location and restoration systems).</td>
</tr>
<tr>
<td>(iv) Facilitate demand response and flatten peak loads (direct utility control of selected loads thru tele-switching, real-time pricing).</td>
</tr>
<tr>
<td>(v) Improve ancillary services such as frequency and voltage regulation, load following (through bulk storage, distributed storage).</td>
</tr>
<tr>
<td>(vi) Reduce power system carbon dioxide emissions and other environmental emissions (through enabling off-take from more variable renewable energy and other distributed renewable generation options).</td>
</tr>
</tbody>
</table>


IV. THE NEXT PHASE

103. There can be many reasons for countries not to achieve the increasingly aggressive VRE targets in the coming years and grid stability problems are one set of reasons. Lessons learned from experience and evaluations show that a suitable regulatory framework, a more flexible generation capacity, energy storage capability, demand response, enhanced grid flexibility and smart grid technologies will facilitate VRE integration in existing and expanding power systems. These measures are consistent with ADB energy policy and can broaden the repertoire of ADB interventions.

A. Support a New Policy and Regulatory Framework

104. Small power systems. The involvement of many development partners in Pacific SIDS reinforces the need for harmonizing technical standards for VRE facilities and grid infrastructure projects to improve operations and reduce inventories. This has been attempted in Cook Islands and can be explored for other SIDS. Encouraging the use of fast-response batteries would become increasingly important as SPV penetration rise. Additionally, regulatory frameworks to attract private sector investment may be required in many SIDS.

105. Large power systems. With increasing VRE penetration, an important policy and regulatory objective would be to enable non-VRE components of power systems become more flexible to accommodate rising supply side variability, support smooth system operation, maintain grid stability, and keep voltage and frequency variations within tolerable limits. Many such regulations are required even in the absence of grid-connected VRE capacity but may need to be strengthened to ensure grid reliability and power supply quality at high levels of VRE penetration.

106. A key challenge will be to find ways to keep power utilities solvent when VRE and other distributed generation capacity increases. As grid integration costs in a power system are likely to rise as VRE penetration rises (ceteris paribus), a regulatory framework that can account for the cost structure of
VRE integration, and provide a good (and informed) basis for sharing of costs between power utility and VRE developer, will become increasingly important. It would need to encourage a market for ancillary services, allow for new services and revenue channels, and support new business models.

107. A market structure that (among others) allows for flexible resources to provide services to meet electric grid requirements can take many forms and depends upon system characteristics and other local conditions. For example, there may be a need to invest in very fast responding systems that provide critical capacity when needed, or transmission providers and energy storage facility developers could be allowed to enter into long-term agreements. Such policy initiatives would need to encourage (among others) investment in energy storage, smart-grid technologies and approaches, efforts to increase flexibility of some power plants, and demand response measures.

B. Adapt Technical Options to Small Power Systems

108. ADB has emphasized better VRE resource assessment and battery storage which helps address the energy security concerns of SIDS. ADB can also facilitate the harnessing of two VRE resources to improve temporal grid flexibility. Given the broad trend of falling costs of VRE and battery technologies, coupled with improved performance, it is very likely that the lessons from the Tokelau archipelago can be useful to other SIDS.

109. In some SIDS, the power utility is considering the connection of large off-grid VRE capacity on to an existing mini grid (for instance, in the Republic of Marshall Islands). In doing so, the transmission or sub-transmission systems could become congested at certain points, and call for measures to reduce or eliminate VRE curtailment. In such cases, it appears the feed-in-tariffs that take into account the cost of integration can be considered.

C. Enlarge the Range of Technical Options for Large Power Systems

110. ADB has provided sector regulatory and policy advice, and supported investment and capacity development for grid strengthening, grid extension, smart grids, and electricity storage in large power systems. Opportunities for ADB support in these areas will most likely increase. However, there are other measures that facilitate VRE integration in large power systems that ADB has not supported to date. These measures are consistent with the ADB energy policy, and pertain to (among other) increasing generation flexibility of thermal power plants, using hydropower plants for storing VRE output, and exploring opportunities for other energy storage technologies, facilitating demand response and improving grid flexibility.

1. Improve Generation Flexibility

111. Evidence from the United States shows that improved generation flexibility of coal-fired power plant units can generate net system-wide benefits in terms of increased absorption (or reduced curtailment) of VRE power, CO2 emission reduction, and cost saving. This provides a basis for ADB to consider supporting similar efforts in countries with significant coal-fired capacity.

112. On the basis of readily available information, the most likely candidate countries are the PRC, India, and Kazakhstan where coal-fired generation accounts for more than 70% of total utility generation. Some VRE off-take problems have been experienced to date in the PRC and India. Although VRE share in Kazakhstan remains low, it is expected to rise fast given the target of reaching a 50% share from renewables by 2050.32 Kazakhstan also intends to enhance energy connectivity across borders and tap into more VRE such as solar and wind.33 Other possible candidate countries are Indonesia, Malaysia, and

32 The country’s wind resources can provide more than 10 times the present level of electricity requirements.
the Philippines, where at the national level, the share of coal fired generation in 2012 was 49%, 41%, and 39% respectively—although it could be significantly higher in some power systems in these countries.

113. ADB can prepare a comprehensive database that covers each existing coal-fired unit in the high-coal-share power systems in these countries. From the perspective of identifying good prospects for improving generation flexibility, the ADB database can include the following information (among other aspects): capacity, vintage, type of boiler (horizontal or pendant), sub-critical or super-critical steam characteristics, start-stop characteristics, minimum generation level, actual heat rates and emissions at different load points, staffing, and normal operating practices. A suitable screening system coupled with power system simulations can help prepare a short-list of the best candidates among existing coal-fired units. Such an exercise would provide a basis for ADB to design projects that include (i) investment in selected existing coal-fired power plant units, which may require technology transfer; and (ii) training programs for power plant operators in existing coal-fired units which requires learning from good international practices. As necessary, ADB can continue to conduct policy dialogue and advice on regulatory and pricing matters.

2. Support Energy Storage in Hydropower Facilities

114. Many power utilities are generally familiar with hydropower, which can provide energy storage—but has not normally been considered for this.

115. Conventional hydropower plants. Experience in Europe shows that reservoir management practices of conventional hydropower plants can be modified to store power generated in wind farms. It is worthwhile investigating whether or not such complementarity between wind resource and hydro flows can be tapped in developing Asian countries that have adequate wind resources and conventional hydropower plants with storage reservoirs.

116. On the basis of readily available information, it appears the most likely candidate countries are (i) the PRC which has more than 40 hydropower plants with each having 1000 MW or more of generating capacity; and (ii) India which has more than 10 hydropower plants with each exceeding 1,000 MW capacity. Both countries have made significant progress in installing and operating wind power turbines; and wind resource assessments to date show that both the PRC and India have large wind power potentials.

117. Similar opportunities can arise in some other countries in developing Asia. Large hydropower power plants have been set up in Lao People’s Democratic Republic (mainly to export power to Thailand) but wind resource potential had not been assessed sufficiently thoroughly in either country at least until a decade back (Pholsena et al, 2004). Although more recent estimates indicate that wind power potential is reasonably high in Thailand (Energy Procedia, 2013), further wind resource assessments would be required in both countries. Many countries in central Asia have sizeable hydropower potential, and given the escalation of water management challenges in the subregion, some are considering diversifying their power generation sources (for example, Kyrgyz Republic). Wind energy appears to be one of the prime candidates and wind power assessments would be required first.

118. ADB can list the candidate power systems for harnessing of hydro and wind complementarity and prepare a comprehensive database that covers each large hydropower plant. The information required for hydropower plants can cover relevant environmental parameters and reservoir management parameters. The environmental parameters can help ADB gauge whether or not the consequences of

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34 Evidence for similarly storing power from SPV systems is not available.
35 This refers to plants where water flow can be regulated and excludes plants that have only diurnal water storage capacity.
36 In the southeast PRC alone, the wind power potential exceeds 50,000 MW (NREL, 2002). In India, the wind potential has been assessed to be up to 102,000 MW (Center for Wind Energy Technology, 2013).
changing reservoir management practices and implementing associated safeguard and risk management measures will keep environmental consequences within acceptable limits. The reservoir management related parameters (such as discharge rate, head, spillway and intake point and min-max water level), can help ADB prioritize where drawdown rates can be altered to accommodate intermittence of wind power. Such an exercise can help ADB in designing projects that include (i) investment (if any) to facilitate modified reservoir management practices and coordination with the respective control centers; and (ii) training of hydropower operators, which may require learning from good international practices. As necessary, ADB can continue to conduct policy dialogue and advice on regulatory and pricing matters.

119. **Pumped hydropower storage.** Subject to their meeting environmental and social safeguards and other concerns, ADB can consider supporting investment in new PHS capacity. ADB can also consider providing technical assistance to assess whether or not it is possible to retrofit existing PHS to increase round trip efficiency, and if necessary, further support for retrofitting and training. Such opportunities do exist in the PRC and India, which have sizeable PHS capacity.

120. An interesting implication of increased PHS capabilities can be storing the electricity output of large-scale grid-connected PV capacity, which will be the maximum around mid-day and mid-afternoon, precisely when electricity requirement is low in many developing countries.  

3. **Increase Focus on Demand Response**

121. Given that demand response is a cost-effective GHG-free balancing resource for VRE, ADB can support utilities to urge customers to time-shift certain loads. Such measures however, are more likely to be successful where power supply reliability is good. In countries where power supply reliability is poor—as in many countries of developing Asia—it is worthwhile to examine the relevance of demand response approaches. It is likely demand response approaches are possible in some large urban centers of these countries.  

39 Opportunities for such work however, are anticipated to rise in the coming decades.

4. **Improve Grid Flexibility**

122. The reduced need for reserve capacity and spinning reserve has traditionally provided the rationale for integrating power systems. The intermittence of wind and solar energy resource at a particular location, and the differences in wind and solar energy output across different locations, reinforce the need for integrating grid operations across power systems. The combined integrated power system can absorb more VRE output than the sum total of VRE outputs that the individual (prior to integration) power systems can offtake.

123. ADB can support client countries explore possibilities for temporal and spatial grid flexibility of VRE. The spatial grid flexibility that comes about when two or more distinct power systems are interconnected, would require that the combined system has good voltage and frequency regulation, operates within thermal limits and remains stable. Such interconnections would call for other measures that hinge on good communication and coordination between the control centers of different power systems.  

38 However, it is difficult to see such opportunities exploited in the near term owing to off-peak power deficits, for example, in certain parts of India.

39 An example is a demand response program launched by a distribution utility in Delhi, India. The objective was to reduce the power purchase bill by reducing the need to purchase high priced power at peak times. The distribution utility implemented an industrial and commercial peak shaving automated demand response system (Memoori Business Intelligence. 2015).

40 Some such measures that would be required for interconnecting power systems with or without VRE, would be: (i) metering of transmission lines to neighboring control areas and monitoring of incoming and outgoing power flows; and (ii) continuous tracking of and balancing of load, generation and exchanges with other control areas for better real-time adjustments to maintenance scheduling and transmission loading. Pre-agreed emergency protocols and similar reliability standards facilitate operation of interconnected systems. A uniform regulatory environment that governs the functioning of all concerned power systems facilitates coordination.
124. Whether or not interconnected power systems are in the same country, a basic concern would be that the reliability problems of one power system should not adversely affect the performance of the other interconnected system(s). For even when interconnected power systems are in the same country, there can be significant differences in the reliability standards among them. Such technical challenges multiply for inter-country interconnections owing to differences in regulations, control schemes, and technologies. Likewise, challenges for information interchange and institutional coordination also increase for interconnection of neighboring country power systems.

D. Conclusion

125. It is noteworthy that (i) renewable energy has a prominent place in IEAs bridge scenario and that VREs are the most abundantly resourced renewable energy; and (ii) climate change mitigation plans will become increasingly ambitious for most (if not all) countries and call for increased VRE capacity. Additionally, with improvements in performance and cost reductions, VRE technologies are becoming increasingly competitive—a trend that is anticipated to continue in the coming years. Against this background, it is highly likely that VRE penetration increases in the foreseeable future.

126. To date, ADB supported projects have introduced a few approaches to facilitate grid integration of VREs. In addition to grid strengthening and grid extension—among the traditional areas of ADB’s power sector interventions—ADB has approved projects that include support for the following: (i) battery storage in SIDS and other countries; (ii) demand response from selected consumers to time-shift loads in SIDS; and (iii) capacity building and investment in some smart grid technologies in countries with large power systems. Policy and regulatory support has been largely with the objective of providing a level-playing field to VRE developers and operators. ADB must continue to support these approaches, as appropriate, in SIDS and other countries.

127. Some of the notable omissions that ADB can consider supporting (where relevant) are the following: (i) instituting a suitable power market structure; (ii) increased flexibility of power generators; (iii) demand response programs which can possibly be combined with energy efficiency programs; and (iv) large-scale energy storage. There can be situations where with increased flexibility of an existing coal-fired power unit, CO₂ emissions per unit of generation from that particular unit increase while CO₂ emissions reduce system-wide. In such situations, ADB needs to be willing and able to support flexibility in existing coal-fired power units. Likewise, and subject to all environmental, social, and other considerations (including safeguards), ADB could support modifications in conventional hydropower and PHS for utility-scale energy storage.

128. Although ADB has supported interconnections between two or more power systems—mostly within a country but also across international boundaries—the stated rationale has never related to exploiting spatial grid flexibility benefits of VRE. Yet, it is clear that VRE complementation provides a good rationale for strongly interconnecting grids and enabling synchronized operation. This can contribute to achieving ADB’s targets for supporting climate change mitigation and is consistent with the rising concerns over global and regional public goods.

129. All these measures are compatible with the existing ADB energy policy, and will become increasingly important as VRE investments grow. Policy dialogue must begin sufficiently early so as not pose a binding constraint that curtails VRE output or impedes investment in VRE capacity.
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Increasing Penetration of Variable Renewable Energy: Lessons for Asia and the Pacific
Many countries have set aggressive variable renewable energy (VRE) targets for mitigating climate change. Lessons learned from experience and evaluations show that a suitable regulatory framework, a more flexible generation capacity, energy storage capability, demand response, enhanced grid flexibility and smart grid technologies will facilitate VRE integration in existing and expanding power systems. These measures are consistent with ADB energy policy and can broaden the repertoire of ADB interventions.

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Contact Information
Independent Evaluation Department
Asian Development Bank
6 ADB Avenue, Mandaluyong City
Philippines 1550
www.adb.org/evaluation
Email: evaluation@adb.org
Telephone: (+63-2) 632 4100
Fax: (+63-2) 636 2161