CONNECTED & FLOWING

A RENEWABLE FUTURE FOR RIVERS, CLIMATE AND PEOPLE

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Please cite as:
Opperman, J., J. Hartmann, M. Lambrides, J.P. Carvallo, E. Chapin, S. Baruch-Mordo, B. Eyler, M. Goichot, J. Harou, J. Hepp, D. Kammen, J. Kiesecker, A. Newsock, R. Schmitt, M. Thieme, A. Wang, and C. Weber, 2019. Connected and flowing: a renewable future for rivers, climate and people. WWF and The Nature Conservancy, Washington, DC

ISBN: 978-2-940529-94-0

CONTENTS

EXECUTIVE SUMMARY

Due to the renewable revolution, power systems can now be low carbon, low cost, and low impact on rivers, the environment and people

The world faces multiple critical and intertwined challenges: expanding electricity generation to meet the needs of growing economies and to supply power to the more than one billion people who currently lack access while reducing greenhouse gas emissions to nearly zero by 2050 – all while maintaining the integrity of our world's ecosystems, including conserving the planet's remaining free-flowing rivers.

Today, the world has a great opportunity to solve these challenges, made possible by the renewable revolution — featuring rapidly falling costs for wind and solar generation and storage technologies, and significant advancements in energy efficiency, demand side management, and grid management. In addition, great progress has been made on the accessibility of tools that allow governments to strategically plan power systems so that the expansion and operation of projects can maximize synergies and minimize negative impacts.

We can now envision a future in which electricity systems are accessible, affordable and powering economies with a more sustainable mix of renewable energy technologies — including solar, wind, storage and low-impact hydropower. For the first time, there are viable renewable alternatives to the high-impact hydropower dams that are currently proposed on many of the world's remaining free-flowing rivers – a development path that could trigger a range of negative impacts, including displacement of communities, and the loss of productive freshwater fisheries and much of the sediment needed to keep economically crucial deltas above the rising seas.

This report describes how the world can tackle these intertwined challenges and support global efforts to achieve the Sustainable Development Goals (SDGs) and the targets under the Paris Agreement, by moving rapidly toward electricity systems that are:

1. **Low carbon.** The imperative to decarbonize energy systems, and economies in general, becomes increasingly clear with each passing year. A stable climate – and prosperous societies and healthy ecosystems – requires that electricity systems move rapidly to being low carbon and efficient and that some sectors, such as heating and transportation, be electrified.
2. **Low cost.** Power systems that are low carbon and low impact must also meet countries' power demands with electricity that is reliable and affordable. Furthermore, social equity demands that energy investments ensure access to the more than one billion people that still lack access to reliable electricity. In fact, the short construction times, versatility, and low costs of new renewables allow countries to accelerate access to electricity.
3. **Low impact.** Nearly all options for producing energy have some negative impacts on communities and the environment. But, options for low-impact systems are becoming increasingly feasible and various best practices can be applied to further reduce impacts, particularly on the world's remaining free flowing rivers.

Achieving this vision will not happen by pre-judging what technologies and mixes of energy generation should be deployed. Decisions about future electricity systems should follow a process to identify options that are consistent with the principles above. Any mix of sources that can meet those principles (low cost, low carbon and low impact) will work for people, nature and the climate.

In practice, we believe that electricity systems that meet these principles will increasingly be those that avoid the significant tradeoffs associated with high-impact hydropower projects. However, avoiding those tradeoffs and impacts does not equate to an end to hydropower development, but to a significant shift in its role and competitive niche. Hydropower projects provide a range of services that can help balance power systems and facilitate the integration of a higher share of wind and solar generation — both through the reoperation of existing hydropower and through strategically designed new projects, including off-channel pumped storage, that avoid the significant tradeoffs associated with past development. These carefully planned projects will provide lower risk and higher value to investors and developers, while delivering greater overall values to countries and communities.

The urgent need to expand access to energy while decarbonizing power systems

To avoid exceeding a global temperature rise above 1.5°C, the IPCC reports that the world will need to cut global CO_2 emissions by approximately 40-50%

KEY POINTS

- The costs of wind, solar, and battery storage have dropped dramatically in recent years - and are continuing to fall. Renewable sources represented two-thirds of new global power generation capacity in 2018, led by wind and solar.
- The global technical potential of utility-scale, low-impact wind and solar is 17 times the renewable energy targets that countries have committed to under the Paris Agreement, and well distributed. This should allow almost all countries to achieve power systems that are low carbon, low cost, and low impact on social and environmental resources.
- Lowering the total number of new hydropower dams because of greater investment in wind and solar can reduce negative impacts on rivers and avoid fragmenting tens to hundreds of thousands of kilometers of free-flowing rivers globally, depending on how development unfolds within river basins.
- Planning tools that integrate capacity expansion models with models to guide low-impact siting of new renewables can help decision makers design systems that are low carbon, low cost and low impact.
- The renewable energy revolution does not signal an end to hydropower development, but a significant shift in its role. Certain types of hydropower are becoming less competitive and the rise of reliable alternatives should diminish the need for high-impact dams. However, low-impact hydropower plants, which provide storage capabilities and flexibility, could become an important component of the world's transition to deploying considerably more intermittent renewable energies.
- By capitalizing on economic and financial trends as well as improved technologies, we can secure a brighter future for people and nature with power systems that are low carbon, low cost and low impact on rivers and other ecosystems.

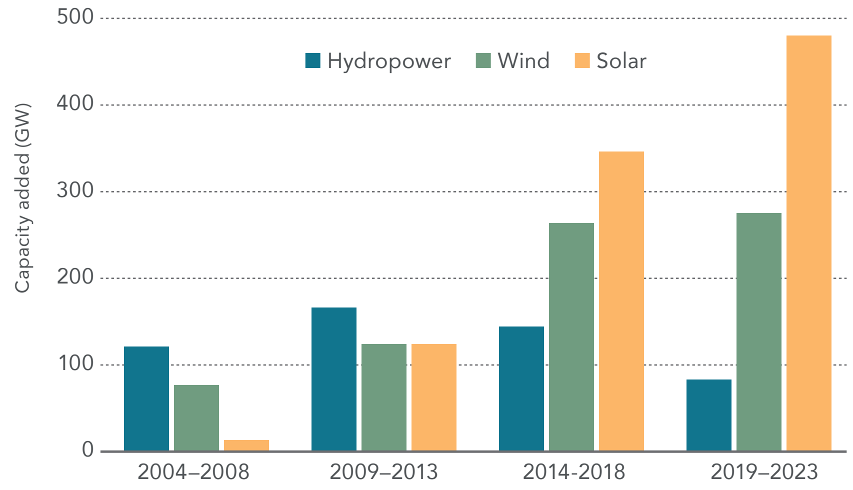
by 2030 and economies will need to become nearly carbon free by 2050. Since electricity generation is a leading source of GHG emissions, decarbonization of power systems is critical to achieve the necessary emissions reductions, especially as electricity generation must increase to provide power to the more than one billion people around the world who still lack access. This will require a rapid transition away from fossil fuels (coal, natural gas and oil) to low-carbon renewables such as wind, solar, geothermal and hydropower. While hydropower has been the dominant source of renewable generation so far, projections of how the world can meet future electricity demand while also achieving climate goals include a massive increase in the proportion of wind and solar, with these sources expected to attain a share of generation comparable to, or exceeding, that of hydropower.

The renewable revolution is rapidly changing the landscape of power systems

The costs for a range of renewable energy sources have dropped dramatically in the past decade. Costs for solar and wind are now approaching US$0.05/kWh – comparable to the low end of fossil fuel cost range and the average costs of hydropower.[1] And costs are projected to decline even further.

Because of these rapid changes in relative costs in recent years, the growth of power generation is now driven by investments in new solar and wind capacity (Figure ES1). Capacity additions of hydropower have been declining since 2013, due not only to the falling costs of competing technologies, but also to a broader set of challenges, including high-profile cancellations, growing hydrological risks, cost and schedule over-runs, technical challenges, and increasing social resistance.

Certain types of hydropower are becoming less competitive, with the rise of reliable alternatives diminishing the need for high-impact dams. However, low-impact hydropower plants that provide storage capabilities and flexibility have a strong role to play in backing up variable sources, such as solar and wind, and providing the ancillary services that contribute to grid stability. Low impact hydropower could still be an important component of the world's transition to deploying considerably more intermittent renewable energies.



ES1. Recent growth in renewables by type

Global renewable power capacity additions, 2004-2023 (from IEA 2017).[2]

The renewable revolution can increase conservation of free-flowing rivers by delivering low cost, low carbon, low impact grids

Projections vary widely of how much hydropower will be developed to meet the 2050 power demand and achieve climate objectives. For example, from a current capacity baseline of approximately 1,200 GW, IPCC scenarios that limit global temperatures to below a rise of 1.5°C have median 2050 projection for global hydropower of 1,820 GW – a level that would result in an additional 190,000 kilometers of river channel being impacted by fragmentation, with more than 70% of the impact occurring in river basins with the greatest fish harvest and the highest richness of fish species[3].

However, the trends in cost and levels of investment for hydropower compared to other renewable technologies, and the potential to retrofit existing dams and re-operate cascades — along with lower projections for hydropower in 2050 such as that of Teske (1,523 GW)[4] — suggest that future hydropower development may be lower. A lower level of development could reduce impacts by 65,000 km. With strategic system planning, impacts could be reduced a further 100,000 km - in total, a nearly 90% reduction in impact on river fragmentation (Figure ES2) – securing the diverse benefits that healthy rivers provide to people and nature.

The ability to substitute wind and solar for a portion of hydropower development hinges on the improving competitiveness of those technologies and the ability of grids to incorporate high levels of variable renewable energy, described in case studies below. But ensuring that this substitution leads to electricity systems that are as low impact as possible requires the widespread availability of wind and solar power in areas with low impacts on social and environmental resources. The global technical potential of low-impact utility-scale wind and solar (on converted lands such as agriculture, degraded land, and rooftops) is 17 times the renewable energy targets that countries have committed to under the Paris Agreement, and well distributed (Figure ES3)[5]. This should allow almost all countries to achieve power systems that are low carbon, low cost, and low impact.

Case studies of low carbon, low cost and low impact grids

A number of recent studies have demonstrated the economic and technical feasibility of grids that are low carbon with expansion dominated by renewables. We further explored the potential of low cost, low carbon grids to be low impact on rivers by integrating capacity expansion models for two countries, Chile and Uganda, with basic landscape modeling of the environmental values of rivers.

- In Uganda, a scenario that avoided future hydropower dams within national parks had no impacts on power system costs compared to the reference, or business as usual (BAU), scenario; solar PV and storage would replace the two hydropower plants within a national park that are selected in the reference scenario.
- In Chile, the reference (BAU) scenario included both coal and a significant expansion of

ES2. Hydropower expansion and impact on rivers

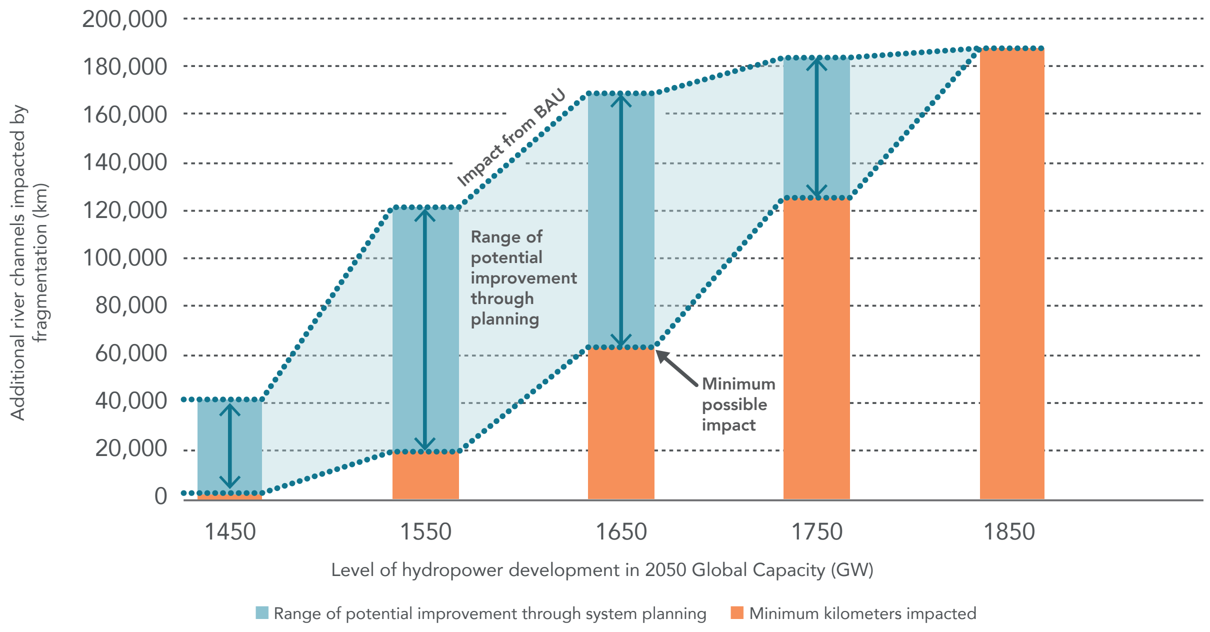


Figure ES2. Potential improved outcomes for global rivers through substitution of other technologies for hydropower (moving from right to left) and through system planning to optimize between generation and environmental performance within river basins (blue shaded area within any given level of development). The top of the combined bar represents the level of impact from business-as-usual development of hydropower dams for a given total level of global hydropower capacity by 2050 and the top of the red bar represents the minimum impact possible at that level of development[i] (From Opperman et al. 2015 based on dam database from Zarfl et al. 2015)[6].

hydropower. Low carbon scenarios that also avoided developing new dams on Chile's remaining free-flowing rivers had costs that were only 1.5–2% higher than the reference scenario, with a carbon intensity that was one-quarter that of the reference scenario.

These examples demonstrate how the integration of capacity expansion models with landscape models to guide siting can reduce the impacts from hydropower within power systems. A range of other best practices can be used to further minimize impacts from hydropower generation, including rehabilitating and retrofitting existing hydropower dams, re-operating dams and cascades, and adding turbines to non-powered dams. Overall, incorporation of the mitigation hierarchy into regional planning for new renewable projects can reduce impacts and conflicts, contributing to conservation and facilitating faster permitting and development.

What the world needs to do to achieve the low carbon, low cost and low impact vision

Accelerating the renewables transition requires the removal of barriers, including policy and regulatory reforms, redirecting financial flows towards new renewables, and technological innovation. There are successful examples for all of these that can be emulated by other countries. Many governments need to modernize their energy-sector policies to take full advantage of the renewable revolution, for example by committing to renewable energy targets and/or introducing targeted auctions for renewables to identify least-cost options.

Financing of new renewables not only needs to be scaled up dramatically, it also needs to include funding for system planning, via both domestic budgets but also through support from international financial institutions. The integration of capacity expansion models with models to guide siting of new renewables can help decision makers understand tradeoffs of different options and identify those options that perform well across a range of objectives (see Box ES-1).

i Note that the bar for 1,850 GW is depicted as having no range of potential improvement from system planning, but that is because that level of development requires building all the dams in the database and thus we can't model different configurations

ES3. Global map of potential hydropower and potential generation from low-impact wind and solar

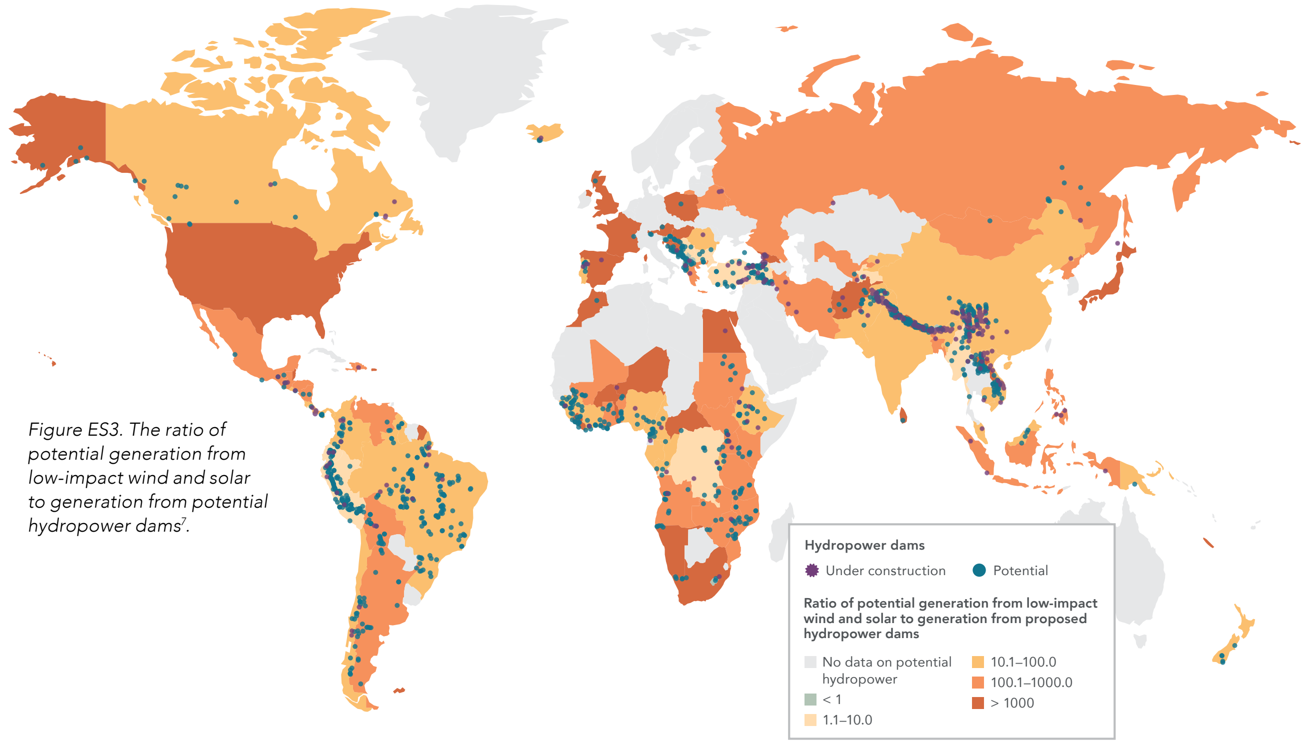


Figure ES3. The ratio of potential generation from low-impact wind and solar to generation from potential hydropower dams[7].

BOX ES-1

SUSTAINABLE POWER SYSTEMS FOR THE MEKONG RIVER BASIN

The Mekong River supports the world's most productive freshwater fishery and delivers sediments that maintain the physical integrity and productive ecosystems of the Mekong Delta, a crucial part of Vietnam's economy and regional food security, and home to 21 million people.

Hydropower has been a primary source of electricity for Mekong countries, but studies show that a continuation of the current hydropower trajectory would cause the loss of nearly half of migratory fish biomass. Deprived of sediment trapped behind dams and subject to other pressures, the delta could be more than half underwater by the end of this century.

Recent studies suggest that the region could meet future power demand with considerably lower development of hydropower than business-as-usual projections. The integration of capacity expansion models with models to guide low-impact hydropower siting provided strong evidence that the Mekong region can develop low carbon, low cost power systems that do not require dams on the mainstem or on the few remaining free-flowing major tributaries – and that any additional hydropower can be sited so as to have minimal impact on fisheries and sediment per unit of hydropower produced.

Although there are signs that the renewable revolution is taking hold in the Mekong region, decisions in the next few years on highly impactful dams such as Sambor could preclude more balanced outcomes. Coordinated and proactive policies and planning are needed to ensure that countries pursue a more sustainable energy path.

CONCLUSION

Within a very short time, the vision of low-cost, low-carbon, and low-impact power systems has become a real possibility. Much of the renewable energy revolution is already underway. Although this transition received some initial momentum from policies, it is now driven as much by technological innovation and marketplace competition as by policy[8].

We can not only envision a future where electricity systems are accessible, affordable and powering economies with a mix of renewable energy technologies — including solar, wind, storage and low-impact hydropower—we can now build that future. Growing electricity demands and climate objectives can be achieved while avoiding the negative impacts on the world's remaining free-flowing rivers posed by high-impact hydropower.

Achieving the vision will require policy, financial, and technical innovations across all countries. Fortunately, at this stage the feasibility of low-carbon, low-cost and low-impact systems — and the benefits of achieving them — are becoming clear, creating powerful incentives for different groups of stakeholders (see Box ES-2). These stakeholders need to take proactive and collaborative action to ensure a rapid transition to more sustainable power systems. If various constraints delay the transition by even a decade, the health and productivity of rivers such as the Mekong, Irrawaddy, and Amazon — and dozens or hundreds of others around the world — will decline due to significant impacts that are both near-permanent and avoidable. It would be a great tragedy if the full environmental benefits of the renewable revolution arrived just a few years too late to safeguard the world's great rivers and all the diverse benefits they provide to people and nature.

To avoid those losses — and seize the profound opportunity before us — we hope this report serves as a call to action for collaborative acceleration: working together, governments, financial institutions, the private sector, civil society and scientists can build the tools and mechanisms necessary to catalyze rapid delivery of a more sustainable energy future for the climate, rivers and people.

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ENDNOTES

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8 IRENA (2019). Innovation landscape for a renewable-powered future. International Renewable Energy Agency, Abu Dhabi.

BOX ES-2

KEY CONTRIBUTIONS TO A SUSTAINABLE ENERGY FUTURE

- Governments can (1) implement system-scale planning and licensing focused on integrated power systems to identify and develop those that are low cost, low carbon and low impact. Through this, countries can reassess plans for hydropower to factor in the full value of rivers and consider the availability of lower impact alternatives; and (2) create competitive frameworks to accelerate the renewable energy revolution to help them meet international commitments, most importantly national contributions to the Paris Agreement, SDGs, and CBD targets.
- Developers can facilitate the transition by supporting more comprehensive upstream planning and by improving their own project assessments using sustainability protocols and safeguards. Developers will benefit from a pipeline of lower-risk projects and, specifically for the hydropower sector, from providing higher-value ancillary services.
- Financial institutions can also support more comprehensive planning as a way to develop a pipeline of lower-risk projects, focusing their lending on opportunities emerging from such plans, and requiring their clients to apply ambitious sustainability protocols and safeguards. Making direct funding available for such activities can be critical. Financiers will benefit from lower-risk projects and, particularly relevant for development banks, accomplish diverse objectives, including multiple SDGs.

Chapter 1

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INTRODUCTION

The world faces a set of critical and intertwined challenges. We must expand electricity generation to meet the needs of growing economies and to supply power to the more than one billion people who currently lack access.

Simultaneously, the climate change crisis requires us to cut greenhouse gas emissions to nearly zero by 2050 — a complicated challenge as electricity production is among today's leading sources of greenhouse gases — all while maintaining the integrity of our world's ecosystems, including preserving the planet's remaining free-flowing rivers.

Today, the world has a great opportunity to solve these challenges. By capitalizing on economic and financial trends as well as improved technologies, we can secure a brighter future for people and for nature with power systems that are low carbon, low cost and low impact on rivers and other ecosystems.

This brighter future has been made possible by the renewable revolution — featuring rapidly falling costs for wind and solar generation and storage technologies, and significant advancements in energy efficiency, demand side management, and grid management. Furthermore, great progress has been made on the accessibility of tools that allow governments to strategically plan power systems so that the expansion and operation of projects can maximize synergies and minimize negative impacts.

We can now envision a future in which electricity systems are accessible, affordable and powering economies with a more sustainable mix of renewable energy technologies — including solar, wind, storage and low-impact hydropower. For the first time, there are viable renewable alternatives to the high-impact hydropower dams that are currently planned on many of the world's remaining free-flowing rivers. This business-as-usual development path would trigger a range of negative impacts, including the displacement of many communities and the loss of productive freshwater fisheries and much of the sediment needed to keep economically crucial deltas above the rising seas. But the renewable revolution means the world no longer needs to accept such dramatic tradeoffs to meet our growing electricity demands and climate objectives.

This report explores how a set of planning approaches, and policy and financial mechanisms, can ensure that the world benefits from the opportunity in the renewable revolution by accelerating the arrival of power systems that are simultaneously low carbon, low cost, and as low impact as possible.

The vision that underpins this report is essentially agnostic to specific energy technologies or sources. It acknowledges that nearly all forms of generation can cause some negative impacts to environmental and social resources and that a rapid proliferation of renewable sources poses its own risks if not planned and implemented in a coordinated way. Rather than pre-determining or pre-judging options, this vision is based on a set of principles.

To tackle these intertwined challenges and support global efforts to achieve the Sustainable Development Goals (SDGs) and the targets under the Paris Climate Agreement, the world must move toward electricity systems that are:

1. **Low carbon.**
   The imperative to decarbonize energy systems, and economies in general, becomes increasingly clear with each passing year. A stable climate — and prosperous societies and healthy ecosystems — requires that electricity systems move rapidly to being low carbon and efficient and that some sectors, such as heating and light-duty transportation, be electrified, a transition that will become more feasible as the cost of electric power declines.
2. **Low cost.** This vision requires systems that are affordable, reliable and meet needs for economic growth. Systems that are low carbon and low impact but do not meet these other expectations will not be politically acceptable and thus will not happen. Furthermore, social equity demands that energy investments also ensure access to the more than one billion people that still lack access to reliable electricity. In fact, the short construction times and low costs of new renewables allow countries to accelerate access to electricity.
3. **Low impact.** Nearly all common options for producing energy have some negative impacts on environmental and social resources. But, increasingly, we know the best practices that can reduce these impacts. This vision holds that politically viable, low-carbon energy systems should be as low impact as possible. This can be accomplished by fully evaluating the diverse options for meeting energy needs and quantifying the associated tradeoffs to inform development decisions. Then, best practices can be applied to minimize the impacts associated with the selected option.

Achieving this vision will not happen by pre-judging what technologies and mixes of energy generation should be deployed. Decisions about future electricity systems should follow a process to identify options that are consistent with the principles above. Any mix of sources that can meet those principles (low cost, low carbon and low impact) will work for people, nature and the climate. In practice, we believe that electricity systems that meet these principles will increasingly be those that avoid the significant tradeoffs associated with high-impact hydropower projects, including large-scale relocation of people and major impacts on fisheries, deltas and other valuable ecosystems and services. The rise of credible renewable alternatives will diminish the need for such high-impact dams.

However, avoiding those tradeoffs and impacts does not equate to an end to hydropower development, but to a significant shift in its role and competitive niche. Hydropower projects provide a range of services that can help balance power systems and facilitate the integration of a higher share of wind and solar generation — both through the reoperation of existing hydropower and strategically designed new projects, including off-channel pumped storage, that avoid the significant tradeoffs associated with past development. These carefully planned projects will provide lower risk and higher value to investors and developers, while delivering greater overall values to countries and communities.

A primary theme of this report is that the renewable revolution is not some techno-optimist ideal shimmering in the hazy future. It is happening today and its implications for how the world meets its energy needs are profound: countries can now reliably power their economies with systems that are low carbon with far lower impacts than in the past, including a much reduced need to accept the tradeoffs that come with the loss of healthy rivers.

But economic and technical feasibility does not automatically translate into adoption. Various forms of friction can slow the transition to power systems that are both low carbon and low impact. If these constraints delay this transition by even a decade, the health and productivity of rivers such as the Mekong, Irrawaddy, and Amazon — and dozens or hundreds of others around the world — will decline due to significant impacts that are both near-permanent and avoidable. It would be a great tragedy if the full environmental benefits of the renewable revolution arrived just a few years too late to safeguard the world's great rivers and all the diverse benefits they provide to people and nature.

To avoid those losses — and seize the profound opportunity before us — we hope this report serves as a call to action for collaborative acceleration: working together, governments, financial institutions, the private sector, civil society and scientists can build the tools and mechanisms necessary to catalyze rapid delivery of a more sustainable future for energy, rivers and people.

REPORT STRUCTURE

In **Chapter 2** we lay out this vision and define what we mean by systems that are low carbon, low cost and low impact and describe the urgent need to meet those principles in an integrated way.

In **Chapter 3** we illustrate why this vision is attainable. The chapter reviews the rapidly evolving landscape for different energy technologies and summarizes the renewable revolution, including its drivers and the opportunities it makes possible. We discuss the implications for the hydropower industry and the ways in which it must adapt to meet broader societal goals and expectations.

We conclude by discussing how all of these technologies interact, including the new roles and business models for hydropower that will help enable the renewable revolution.

Chapter 4 shows how the different technologies fit together within power systems, synthesizing modeling and real-world case studies to demonstrate the feasibility of planning for and operating grids that are affordable, efficient, reliable, low carbon and low impact. Because grids are made up of generation sources that must be placed somewhere on the landscape, we then turn to the best practices available to guide the siting, design and operation of projects and systems to minimize impacts on social and environmental values.

Chapter 5 explores the global potential for improved outcomes for rivers by achieving this vision. The renewable revolution makes new pathways possible and integrated planning can identify the mix of generation sources that can be low carbon, low cost and low impact. Best practices in planning and siting can minimize the impacts from the expansion of new projects. The benefit of achieving this vision, in terms of improved outcomes for rivers, ranges from tens to hundreds of thousands of kilometers of river channels.

Chapter 6. The first five chapters make the case that this vision is possible and is already happening in some parts of the world. However, the dramatic acceleration that will be necessary to meet the world's growing demand for electricity, while keeping climate change below 1.5° C and helping to achieve the SDGs will require overcoming key existing and future barriers. In Chapter 6 we recommend a set of regulatory and policy reforms and financial solutions that would enable this vision.

In **Chapter 7** we synthesize all the various themes of the report–from technological improvements to planning and policy–and ground them in one place: the Mekong River basin, a region that, perhaps more than any other, illustrates the diverse values that could be lost if more-sustainable energy development pathways are not found. We show that a more-sustainable path is possible for the Mekong region, but that will require concerted and collaborative action across governments, financial institutions, the private sector and civil society to accelerate the arrival of the renewable revolution.

Chapter 8 provides a brief summary and conclusion, including a review of the roles and opportunities for various entities – including governments, financial institutions and developers – to accelerate the renewable revolution and the benefits that will accrue to them by doing so.

Chapter 2

THE VISION

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Chapter 2

So, how do we meet the growing global demand for affordable electricity to power economies and lift people out of poverty, while drastically reducing carbon emissions and also safeguarding rivers and the abundant and diverse resources and services they provide to society?

KEY POINTS

- **This report describes a vision for how the renewable energy revolution will enable power systems that are low carbon, low cost, and low impact.**
- ***Low carbon:* Although electricity is a leading source of greenhouse gases – and demand is projected to double by 2050 – meeting climate objectives requires the world to cut emissions by approximately 40-50% by 2030 and economies will need to become nearly carbon free by 2050.**
- ***Low cost:* Power systems meeting criteria of low carbon and low impact also need to meet the expectations of citizens, businesses, and governments for electricity that is reliable and affordable (i.e., cost competitive). This will enable access for those who currently lack reliable electricity (approximately a billion people worldwide).**
- ***Low impact:* Although nearly all forms of generation have some environmental and social impacts, a range of best practices can identify low-impact sites and mitigate and compensate for residual impacts on ecosystems and communities.**

The renewable revolution — enabled by the dramatic improvements in wind and solar generation including a steep drop in cost that greatly increases their competitiveness — coupled with best practices for integrated energy planning, provide an unprecedented opportunity to tackle these intertwined challenges.

This report outlines a vision for how the world can make simultaneous progress on increasing affordable electricity generation, reducing emissions, and safeguarding rivers and terrestrial habitats. The vision is essentially agnostic about what technologies should be deployed but, rather, rests on a set of principles. To succeed, the world must move toward electricity systems that are:

1. ***Low carbon*** due to the urgent need to reduce emissions of greenhouse gases (GHGs) to maintain a stable climate and safeguard economies and ecosystems;
2. ***Low cost: affordable, reliable, and equitable,*** satisfying the world's growing demand for electricity, including providing for the more than one billion people that currently lack access — and therefore meeting the basic requirements for political viability; and
3. ***As low impact as possible,*** given that nearly all forms of electricity generation have some unavoidable impacts and tradeoffs.

2.1 LOW CARBON

The imperative to reduce global GHG emissions is becoming more obvious and urgent with each passing year, underscored by two reports released in late 2018. In their special report, *Global Warming of 1.5°C*[1], the Intergovernmental Panel on Climate Change (IPCC) emphasized that the negative impacts of climate change on economies and ecosystems increase considerably if warming exceeds 1.5°C and approaches or surpasses 2°C.

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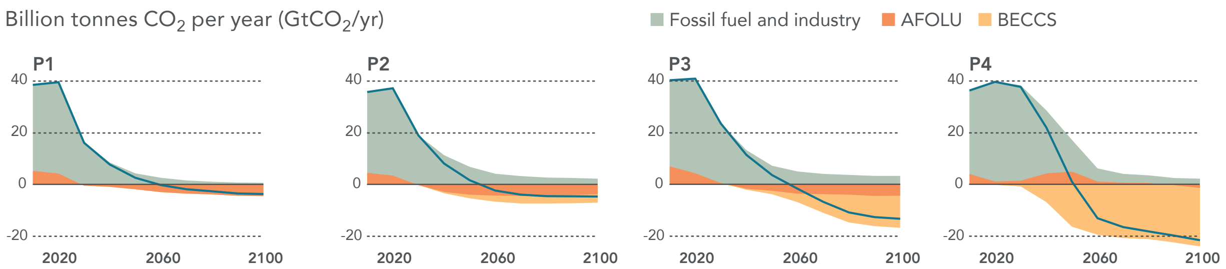
To take just a few examples, under a rise of 1.5°C, 14% of the world's population is projected to be exposed to extreme heat waves while 37% would be exposed under a 2°C rise — a difference measured in billions of people. The number of people living in regions with water stress is projected to be 50% greater under a 2°C rise, compared to 1.5°C. The Fourth National Climate Assessment, issued by 13 agencies of the U.S. government, estimated that, without significant progress on reducing emissions, climate change will cost the U.S. economy US$500 billion per year by the end of the century, equivalent to 10% of the U.S. Gross Domestic Product[2].

Underscoring the urgency of action, the IPCC also concludes that, to avoid exceeding 1.5°C, the world will need to cut emissions by approximately 40-50% by 2030, just over a decade from now, and energy systems and economies will need to become nearly carbon free by 2050.

Beyond specific thresholds, the message is clear: greater warming will lead to greater impacts and thus countries need to reduce emissions at a fast pace — and begin that process as soon as possible (Figure 2.1). Any delay in emissions reductions increases the rate at which they will need to be cut later for the world to remain within lower ranges of climate change, with faster rates of emissions decline posing greater social and economic challenges. Furthermore, delays in emission reductions makes it more likely that even scenarios that ultimately can achieve the 1.5°C goal will require some duration of overshoot — a period of time, often decades, where global temperature exceeds a 1.5°C rise before declining back to that target, increasing the risk of various climate-related impacts on people, economies and ecosystems. The concept of overshoot also highlights that delays in reducing emissions will increase the need for negative emissions, such as the removal of carbon through agriculture, forestry and other land-use (AFOLU) sectors or through bioenergy with carbon capture and storage (BECCS)[3].

Because electricity generation represents approximately one quarter of global GHG emissions, the decarbonization of power systems is one of the primary changes needed to achieve necessary emissions reductions[4]. This will require a rapid transition away from fossil fuels (coal, natural gas and oil) to low-carbon renewables such as wind, solar, geothermal and hydropower. Illustrating the scale of the challenge: fossil fuels are today's leading

2.1. Breakdown of contributions to global net CO2 emissions in four illustrative model pathways



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarboniza-tion of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

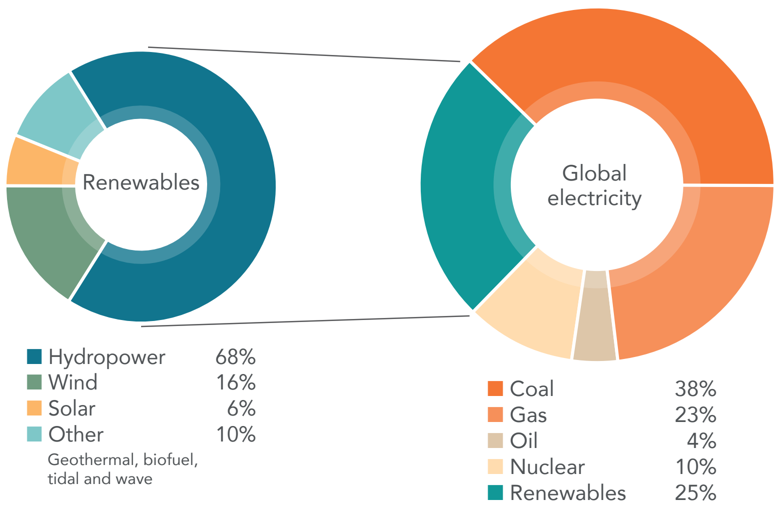
P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

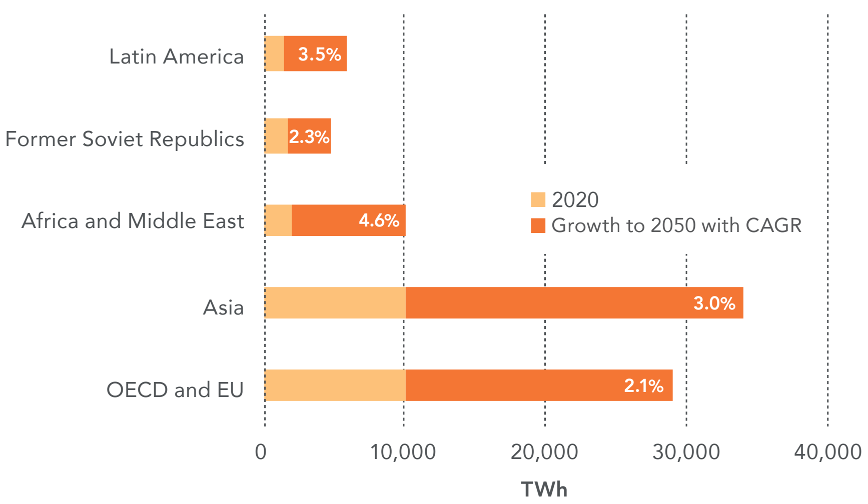
2.1. To achieve climate objectives — and maintain stable economies and healthy ecosystems — emissions of greenhouse gases need to decline considerably and swiftly, beginning within the next few years. Delays in emission reductions will increase the chance of the world overshooting 1.5°C and would require large-scale carbon removal to bring the global temperature increase back below that critical threshold. (adapted from IPCC 2018[5])

2.2. Global electricity and renewables mix

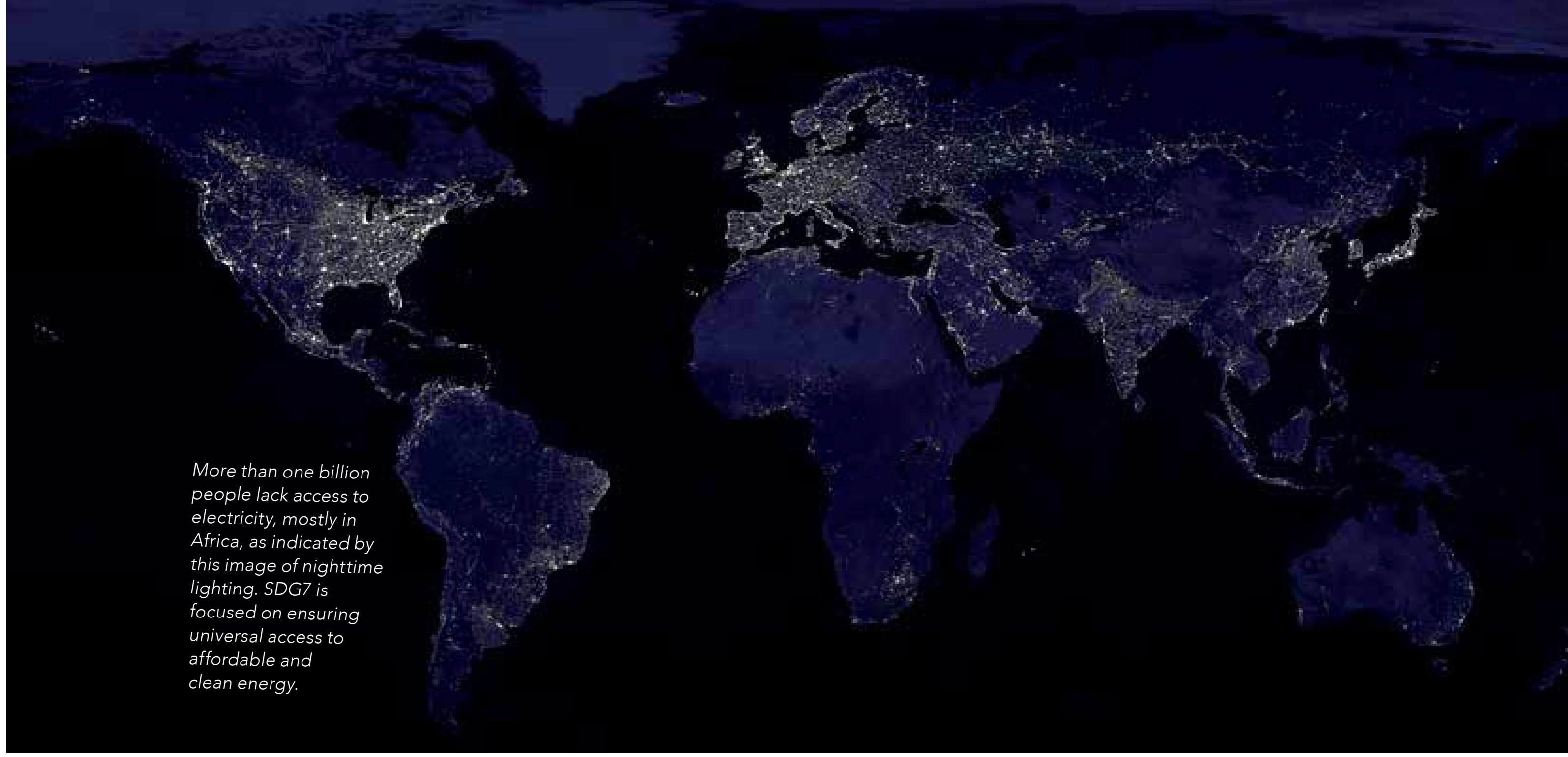


2.2. Global electricity generation by source and renewable generation by source[6]

2.3. Electricity demand by region



2.3. Global electricity demand is projected to more than double by 2050, with greatest growth in Asia. Along with expanding access to electricity, electrification of sectors such as transportation and heating — crucial for reducing GHG emissions — contributes to this rise[7].



More than one billion people lack access to electricity, mostly in Africa, as indicated by this image of nighttime lighting. SDG7 is focused on ensuring universal access to affordable and clean energy.

generation sources representing 65% of the total and still dominated by coal. Renewable sources make up 25% of current global electricity generation, dominated by hydropower at nearly 70% (Figure 2.2), which amounts to approximately 16% of total global electricity generation.

Exacerbating the challenge of achieving a rapid transition away from fossil fuels and toward renewables, global electricity demand is projected to more than double by 2050 (Figure 2.3). Three primary factors will contribute to this growth in electricity demand.

- ***Increasing access.*** Currently 1.1 billion people (14% of the world's population) lack access to reliable electricity, mostly in Africa[8]. Because this lack of access is associated with poorer outcomes for health, education and economic opportunities, SDG7 challenges the world to "ensure access to affordable, reliable, sustainable and modern energy for all."
- ***Meeting energy demand as populations and economies grow.*** Growing populations and economies will contribute to rising electricity demand. With the highest current population and most rapid economic growth rates, Asia will see the largest absolute increase in demand while Africa, with the largest projected population growth[9] and rising living standards, will see the largest proportional increase among continents.
- ***Electrification of other sectors***. Most projections of how the world can achieve the necessary reductions in GHG emissions require that several sectors currently powered directly by fossil fuels — including heating and transportation — become electrified and are then powered by renewable sources of electricity.

Even as demand for electricity increases, most countries have committed to making the transition to low-carbon systems through their Nationally Determined Contributions (NDCs) under the Paris Climate Agreement and, more generally, through SDG7. Lowering total energy demand, such as through technical innovation (e.g., energy efficiency) and demand-side management, can also play an important role in achieving climate targets. In the recent set of scenarios modeled in the IPCC 1.5°report, those that include lowering of energy demand, arising through social, business and technological innovation, require the least reliance on relatively untested carbon removal interventions, such as BECCS — and also entail the lowest tradeoffs between climate objectives and other SDGs (e.g., see P1 in Figure 2.1).

Countries that already generate a high proportion of their electricity from renewables provide insights into potential pathways to achieve climate and energy goals as well as examples of practices for managing grids with a high share of variable renewable energy.

Eighteen countries are currently renewable energy dominated, generating 80% or more of their electricity from those sources. In 14 of these countries, hydropower accounts for more than 80% of renewable generation. Indeed, in only one of these countries is hydropower not the majority of renewable generation. In Kenya, geothermal provides 54% of renewable regeneration and hydropower provides another 43%.[10]

Overall, 48 countries currently generate more than half of their electricity from renewables. For 34 of them, hydropower represents most (>80%) of their renewable generation. Denmark has achieved 60% renewable generation, with 70% of that coming from wind. Denmark is increasingly relying on its integration into the large European grid, which allows it to import and export power as required. A significant part of the back-up for Denmark's wind generation is provided by Norwegian hydropower generators (with a grid that is 97% hydropower).

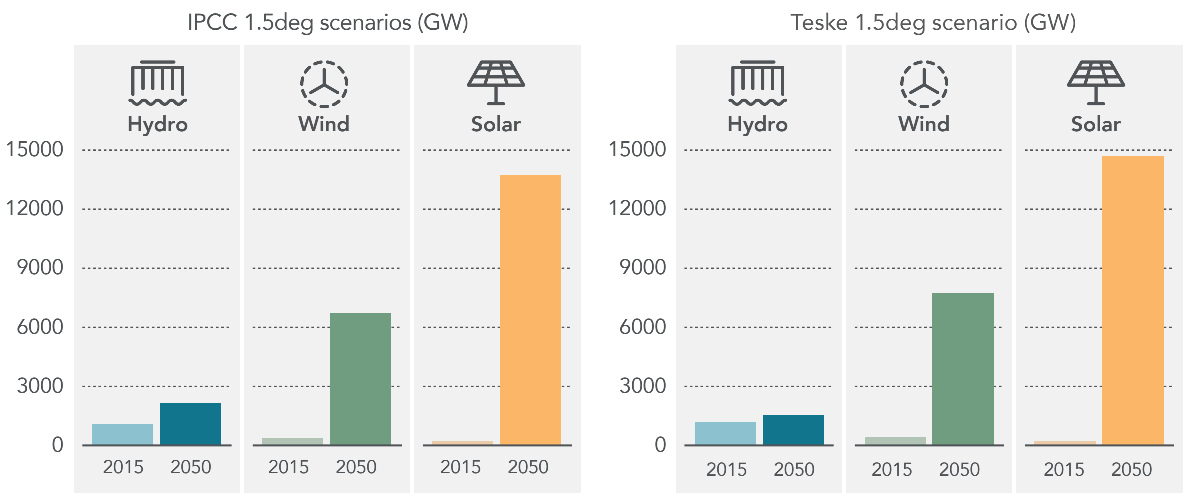
As this summary makes clear, the majority of countries that have achieved a very high level of renewable electricity generation have done so primarily through hydropower. However, a high reliance on hydropower can be in conflict with the third principle — systems that are as low impact as possible on environmental resources.

Although hydropower is generally considered a low-carbon source of generation — the IPCC estimates emissions from hydropower to be only 5% that of natural gas and 3% of coal's emissions[11] — certain types of reservoirs, particularly shallow ones in the tropics, can have significant emissions[12] and recent research suggests that methane emissions from reservoirs may be higher than previously thought[13]. Ongoing research is exploring emissions from reservoirs and this risk remains an important factor to assess during planning and review of potential dams.

While hydropower has been the dominant source of renewable generation so far, projections of how the world can meet future electricity demand while also achieving climate goals include a massive increase in the proportion of wind and solar, with these sources expected to attain a share of generation comparable to, or exceeding, that of hydropower. For example, a projection from Teske et al. (2019) forecasts that wind will increase by nearly 20 times, and solar by more than 60 times 2050, compared to their current levels (Figure 2.4). In this forecast, global wind capacity would reach 5 times, and solar 10 times, the capacity of hydropower[14].

2.4. Projections of the growth of hydropower, wind and solar to 2050. The figure on the left reflects average values from IPCC (2018) scenarios that meet the 1.5°C target by 2100 with low overshoot, while the figure on the right depicts projections from Teske et al. (2019).

2.4. Projections of growth in global capacity of renewables



Although the relative growth of hydropower is projected to be far smaller than those of wind and solar, because hydropower starts from such a large baseline, the total projected increases in capacity are quite high. Various estimates of global hydropower capacity increases range from 300 GW to well over 1,000 GW, representing increases of 25% to more than 100% from the current baseline of approximately 1,200 GW (compare Teske and IPPC projections for hydropower in Figure 2.4).[15]

2.2 LOW COST: POWER THAT IS ACCESSIBLE, AFFORDABLE AND RELIABLE

While this report primarily emphasizes the low carbon and lost impact principles of sustainable power systems, it is clear that power systems meeting those criteria will only be developed if they also meet the expectations of citizens, businesses and governments. Low-carbon, low-impact systems must meet countries' power demands with electricity that is reliable and affordable (i.e., cost competitive). Furthermore, those who currently lack reliable electricity (approximately one billion people worldwide) must gain access. A full exploration of these issues is beyond the scope of this report, but here we provide a short review of key concepts for reliability, affordability and accessibility.

Power systems are planned and operated with the objective of providing a continuous supply of affordable power to meet demand at all times, even during peak hours and even if some components of the system (such as a power plant or a transmission line) may not be available. Since electricity can only be stored at considerable cost, the preference is for power stations to generate exactly what is consumed, or to "follow the load." This requires considerable reserve capacity, flexibility, real-time adjustments and so-called "ancillary services" provided by some types of power plants, to maintain grid stability in terms of frequency and voltage. Hydopower plants are particularly effective at providing these ancillary services.

In well-operated power systems, a central dispatch organization uses short-term demand and supply forecasts to assign generation to the lowest-cost power plants. The dispatchers start with the renewable plants, which have no fuel costs, and then add plants with increasingly higher costs until demand is met. In some systems, there are short-term or spot markets between generating companies, wholesalers, distribution companies and individual large consumers. In others, there is just one large monopolistic utility, which is tasked with optimizing generation internally. The utility may be purchasing part of its supply from independent power generators, or from distributed generation facilities (such as rooftop solar panels) on the basis of "net metering" arrangements.

Recent technical advances are challenging traditional assumptions about grid planning and operation.

For example, distributed generation through small renewable facilities and distributed storage in electric vehicle batteries are changing both the demand and the supply side of the power market and thereby, the "net load" that the utility has to provide. Micro-grids have become more feasible, since they no longer depend on diesel generators. Variable large-scale renewables have made it necessary to consider how to provide and pay for back-up capacities. Smart meters and internet-connected appliances will make demand management easier[16]. The combined implications of all these technical opportunities are still difficult to foresee. Similar to the communications sector, poorer countries may be able to leapfrog certain stages in the development of their power sectors and may never have to invest in large centralized baseload power plants. Distributed generation and storage may also turn out to be more resilient to disturbances, for example from natural disasters.

In general, choosing technologies for grid expansion or replacement of existing capacities should be based on technical feasibility and on costs, as well as on other socio-economic, environmental and political considerations. Costs for the end-user are difficult to compare across countries and technologies, because of factors such as taxes and subsidies, but are frequently between US$ 0.10 and 0.20/kWh. Benchmarks for actual generation costs are either the so-called Levelized Costs of Energy (LCOE, a measure of the average cost of generation from a plant over its lifetime) or the cost offered by generating companies to their off-takers. In Chapter 4, we compare grid expansion scenarios that are low carbon and low impact with business-as-usual scenarios to demonstrate that these principles can be consistent with reliable and affordable electricity.

2.3 LOW IMPACT

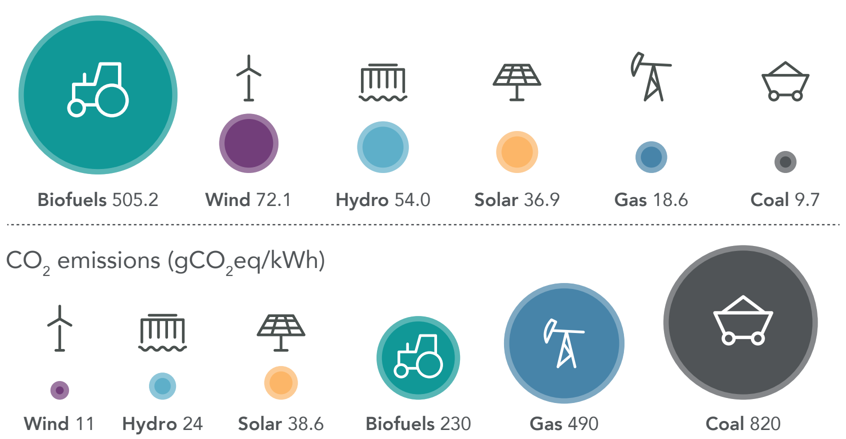
A fundamental premise of current global agreements and many national policies is that the climate impacts from fossil fuel sources of electricity, and other anthropogenic causes, represent a threat to the stability of global economies and ecosystems and thus the world must rapidly move toward decarbonizing energy systems and economies.

Beyond climate, nearly all forms of electricity generation can cause some negative impacts on social and environmental resources. The impacts of traditional energy systems are widely known — notably air quality in the case of fossil fuels and waste and proliferation in the case of nuclear — but this report is premised on the widespread transition of power systems toward renewable sources. Thus, here we provide a concise review of impacts associated with renewable electricity projects.

2.3.1 Wind and solar

Compared to fossil fuels, renewable energy can have larger land use intensity (km^2/unit of energy; Figure 2.5). Therefore, as energy systems decarbonize and shift to renewable sources (with large expansion of wind and solar), demand for land to site renewable power plants will increase. If not well planned and sited, this can exacerbate competition with other land uses such as agriculture, especially in countries where free land can already be highly scarce. Furthermore, renewable development can occur on natural lands, resulting in the conversion, fragmentation and/or degradation of habitats and contributing to the loss of biodiversity. With poor siting, more than 10 million hectares of natural lands worldwide (an area the size of Iceland) could be cleared for wind and solar development as countries seek to meet their NDC commitments[18]. The accompanying roads and transmission lines could also convert and fragment natural habitats. These impacts conflict with SDG15 goals to halt and reverse habitat degradation and loss. The conversion of natural lands is also counterproductive to meeting climate goals, as it can cause stored carbon to be released through the removal of vegetation and soil disturbance. Depending on the siting of wind projects relative to migratory and movement pathways, they can also be detrimental to populations of birds and bats.

2.5. Land-use footprints



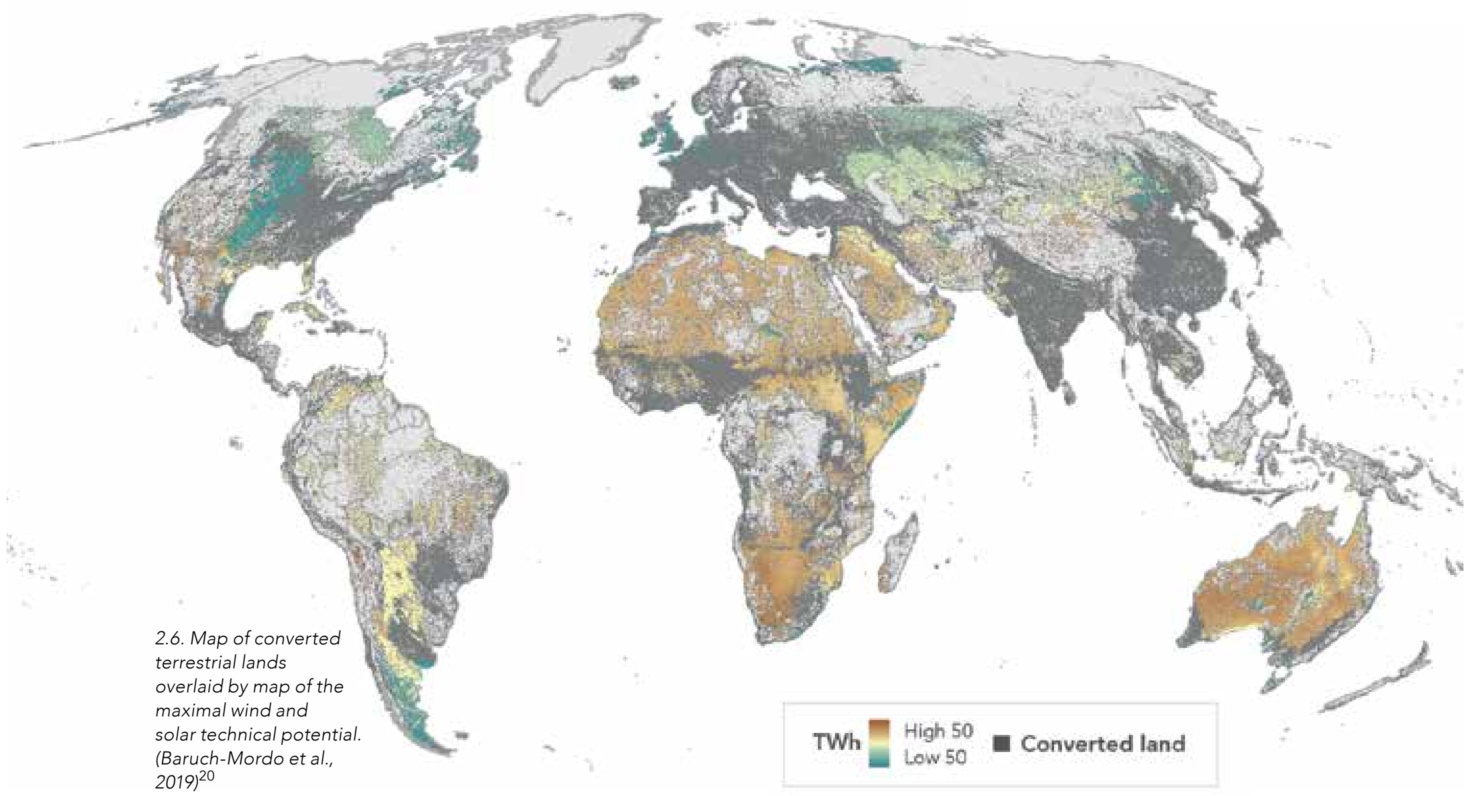
2.5. Land-use footprints for fossil fuels and renewables energy sources adapted from Kiesecker and Naugle (2017).[17]

However, landscape-scale planning can be used to strategically site wind and solar projects to minimize these conflicts with other land uses, habitats and species. Such processes integrate the mitigation hierarchy into infrastructure planning to direct new projects to low-impact sites and maximize the value of mitigation investments[19]. These approaches are reviewed further in Chapter 4.

A key reason that wind and solar can largely be developed in ways that minimize environmental and social impacts is the extensive area of already converted lands that can support renewable energy projects. For example, wind can be highly compatible with agricultural land use, and farmers can diversify their income by leasing their land for wind turbines. Rooftop solar occupies space in urban areas that is largely unused currently and can benefit building owners through net-metering. These examples (agricultural land and rooftops) highlight the great potential to focus the development of renewable energy facilities on already converted lands to minimize impacts on natural habitats, biodiversity and carbon storage. Other examples of converted lands that can support development of renewable energy include pastures, roadways, degraded lands, and reservoirs.

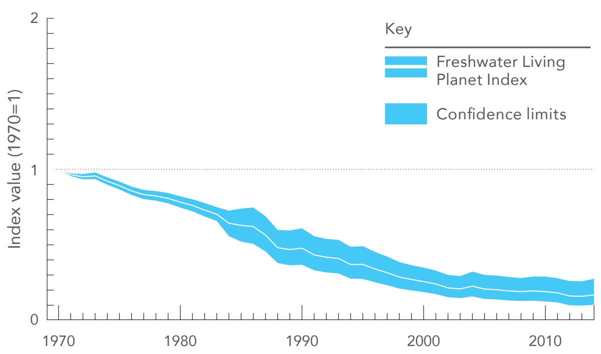
Baruch-Mordo et al. (2018) estimated the global technical potential of utility-scale renewable sources on converted lands (wind, concentrated solar power (CSP) and photovoltaic solar (PV) and rooftop PV), and found the world has 17 times the energy potential on converted lands compared to the Paris Agreement renewable energy targets (Figure 2.6). In addition, this "low-impact" renewable potential exceeded the projected 2050 demands under a

2.6. Global distribution of low-impact wind and solar



2.6. Map of converted terrestrial lands overlaid by map of the maximal wind and solar technical potential. (Baruch-Mordo et al., 2019)[20]

2.7. Living Planet Index for freshwater species



2.7. Populations of freshwater species tracked by the Living Planet Index have declined by 83% on average since 1970, nearly double the rate of decline for populations of species in terrestrial and marine environments.

scenario where all sectors (industry, transportation, etc.) become electrified.[21]

2.3.2 Hydropower

Hydropower has long been the dominant form of low-carbon renewable energy. However, hydropower dams can have considerable individual and cumulative impacts. Dams that create large reservoirs inundate upstream land, including crops and habitats, and displace communities. The World Commission on Dams estimated that 40 to 80 million people had been displaced by dams by 2000[22]. The number of dam-displaced people has grown significantly since then. Additionally, dams are the leading cause of the loss of free-flowing rivers (see Box 2.1), with hydropower dams being a primary cause of the loss of most large free-flowing rivers.

Dams and reservoirs can alter downstream flow regimes, which govern river morphology and critical ecological processes. They also affect the downstream transport of sediment, wood, and nutrients and disrupt the up- and downstream movement of organisms, including fish and other aquatic species. Flow alterations can impact downstream agricultural uses of riverbanks and floodplains, often referred to as flood-recession agriculture. Migratory fish and other species can be particularly affected by dams that act as barriers to and from spawning habitats and, because migratory fish can be dominant within fish harvests, their loss can have major negative impacts on communities that depend on river fisheries[23].

Large reservoirs can trap nearly all sediment, except for the smallest particle sizes, and even small reservoirs can trap many of the larger sediment particles in transport (e.g., cobbles and gravels). Globally, reservoirs trap about a quarter of sediment in transport, resulting in a net reduction in the delivery of sediment from watersheds to oceans of 1.4 billion tonnes/year, compared to levels before people began modifying landscapes and rivers. The cumulative storage of sediment in reservoirs is approximately 100 billion tons[24]. This trapping disrupts the balance of erosion and sedimentation downstream, contributing to the degradation of the river bed (incision), which can isolate the river from its floodplain and lead to the loss of critical river habitats such as sand and cobble bars. Because sediment also transports key nutrients, sediment trapping also reduces nutrient availability to downstream food webs, negatively impacting the productivity of fisheries.

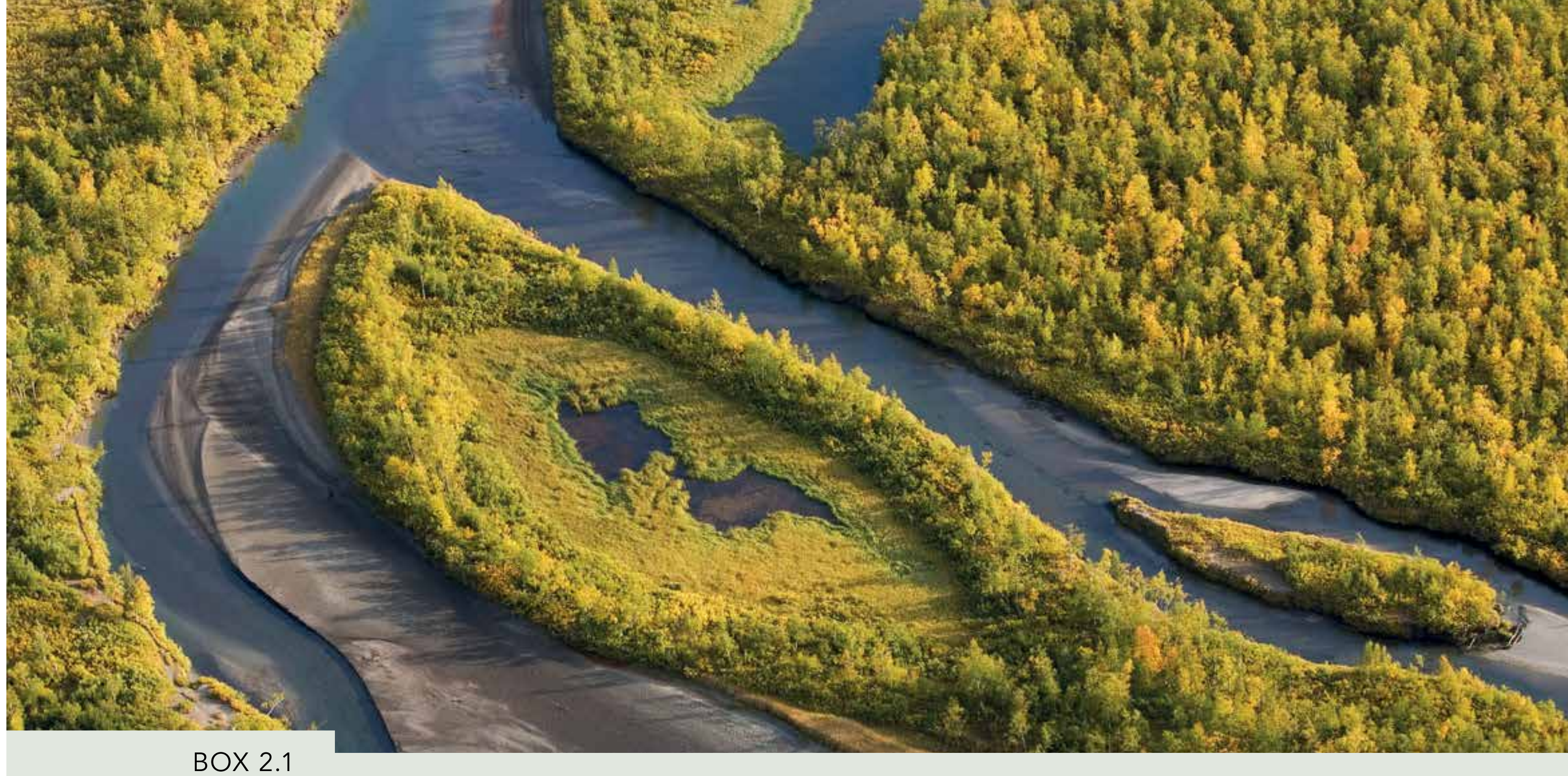
Finally, the retention of sediment within reservoirs deprives downstream deltas of the material they need to keep pace with erosion, compaction, and rising sea levels. Dams are one of the leading causes of shrinking deltas. Deltas are home to over 500 million people (1 out of every 12 people on earth)[25] and support some of the most productive fish harvests and agriculture — for example, the rapidly receding Mekong delta supports half of the rice crop of Vietnam, a top global exporter of rice[26]. If all the proposed hydropower dams in the Mekong basin were built, they would capture nearly all sediment in transport, exacerbating the shrinking of its delta (see Chapter 7 for more detail on the Mekong and its delta)[27].

Because of these various impacts on rivers' habitat, flow, connectivity, sediment and nutrients, dams are consistently ranked among the leading contributors to the population declines of freshwater species and their increased risks of extinction[28]. The populations of freshwater species tracked by the Living Planet Index have declined by 83% on average since 1970 (Figure 2.7), nearly double the rate of decline for populations of species in terrestrial and marine environments[29].

System-scale planning can reduce negative impacts from new hydropower by informing site selection to avoid or minimize losses of environmental and social resources. Environmental flows can also be used to reduce impacts from new hydropower or restore some functions downstream of existing dams.

2.3.3 Achieving low impacts

While a few countries, such as Norway, New Zealand, Iceland and Costa Rica, have achieved the goal that the rest of the world must reach — power



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BOX 2.1

FREE-FLOWING RIVERS

Free-flowing rivers can be defined as rivers "where ecosystem functions and services are largely unaffected by changes to the fluvial connectivity allowing an unobstructed movement and exchange of water, energy, material and species within the river system and with surrounding landscapes. Fluvial connectivity encompasses longitudinal (river channel), lateral (floodplains), vertical (groundwater and atmosphere) and temporal (intermittency) components."

Free-flowing rivers are uniquely important but disappearing – only about one-third of the world's longest rivers (>1,000 km) are still free-flowing with dams as the primary driver of this decline[30]. Rivers are among the most diverse and productive ecosystems on the planet, underpin entire landscapes, and contribute to economic growth, food security and human well-being. Although these benefits are not exclusive to free-flowing rivers, the production of many of them require the natural flow regime and ecosystem processes that free-flowing rivers retain.

- One estimate of the global values of the ecosystem goods (e.g., food in the form of fish), ecosystem services (e.g., waste assimilation), biodiversity, and cultural considerations of inland waters yielded a value higher than the estimated worth of all other non-marine ecosystems combined, despite the far smaller extent of freshwater systems.[31]
- By depositing nutrient-rich silt on floodplains and deltas, rivers have created some of the most fertile agricultural land.[32]
- Inland water fisheries provide the primary source of protein for hundreds of millions of people worldwide and their value is estimated at upwards of US$43 billion.[33]
- 2 billion people rely directly on rivers for their drinking water.[34]
- 500 million people live on deltas that are sustained in part by sediment from rivers.[35]

Intact, healthy freshwater ecosystems are also critical for conserving nature and biodiversity, providing habitats for over one hundred thousand species. Although they represent less than 1 percent of the earth's surface, nearly half of all fish species on the planet can be found in freshwater ecosystems.[36] But rivers aren't only important for the life within them: rivers that are well connected to their riparian areas provide food, critical habitat, and movement corridors to wildlife such as jaguars, elephants, tigers and other species. In fact, entire landscapes, iconic species, and river systems are often connected. For example, the Great Bear Rainforest – the largest temperate rainforest in the world – is shaped in part by salmon swimming from the ocean up the rainforest's free-flowing rivers and creeks. Salmon carcasses (and carcasses that have been "processed" by bears and other consumers) deliver ocean-derived nutrients to fertilize the soil, enhancing the growth of trees.[37] Less easily quantified, but immensely important to people, are the diverse cultural, spiritual, and recreational values sustained by healthy, connected rivers.

generation systems that are nearly 100% renewable — hydropower development has negatively affected a high proportion of their rivers. For example, those countries contain a total of 15 large rivers, but only two can be considered free flowing (see Box 2.1). Although these countries are currently striving for sustainability in management and/or expansion, their overall systems may not achieve the third principle of being as low impact as possible, due in large part to a legacy of investments made under previous regulatory conditions and the technological options available at the time of development.

In subsequent chapters we explore how low-carbon and low-cost power systems can also be low impact, focusing on the three primary ways to move power systems toward low impacts:

- Capacity expansion planning that compares options and their tradeoffs to identify a mix of generation sources that will perform well for sustainability objectives (low carbon, cost, and impacts);
- Best practices for siting projects (e.g., wind, solar, and/or hydropower) to minimize impacts while meeting power system objectives (which could be integrated into capacity expansion planning), and
- Best practices for design and operation of projects.

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Chapter 3

THE RENEWABLE REVOLUTION AND THE CHANGING ROLE FOR HYDROPOWER

Chapter 3

The previous chapter laid out a vision of future electricity systems which are low carbon, reliable, accessible, affordable, and low impact. Here we review the different technologies that will make up these sustainable power systems and current trends in their costs, deployment, risks, and opportunities.

KEY POINTS

- **The costs of wind, solar, and battery storage have dropped dramatically in recent years.**
- **Investment in hydropower has been declining over the past five years, with 19 GW installed in 2017, less than half the level of 2013. Only pumped storage has been increasing during this same time period.**
- **Renewable sources represented two-thirds of new global power generation capacity in 2018, led by wind (49 GW) and solar (94 GW).**
- **The renewable energy revolution does not signal an end to hydropower development, but a significant shift in its role and competitive niche. Certain types of hydropower are becoming less competitive and the rise of credible alternatives should diminish the need for high-impact dams. However, low-impact hydropower plants that provide storage capabilities and flexibility could become an important component of the world's transition to deploying considerably more intermittent renewable energies.**

As we will see, past projections of the expansion of hydropower capacity anticipated a continuation of the rapid development of a few years ago, growth that was largely driven by China and by the competitive costs of hydropower at the time. Today however, the pace of development of new dams has slowed and the role of hydropower is evolving. The declining costs of, and increased investment in, solar, wind and storage — referred to as the renewable revolution — are creating a new landscape for hydropower and for power systems in general. This chapter explores that revolution and the changing role of hydropower, including how it can help catalyze the transition to power systems that are low carbon and low impact.

3.1 TRENDS IN NEW RENEWABLES

3.1.1 Solar and wind: cost, capacity and investment

The costs for a range of renewable energy sources have dropped dramatically in the past decade. For example, the cost of solar photovoltaic electricity declined by 73% between 2010 and 2017 (Figure 3.1)[1]. Because of these rapid changes in relative costs in recent years, the growth of renewable energy generation is now driven by investments in new solar and wind capacity, while the growth of traditional renewable technologies (such as hydropower, geothermal and biomass) is much slower (Figure 3.2). Other technologies, such as concentrated solar power and ocean energies, are still too small in scale to make a major contribution, although they too are poised for technological innovation that may result in lower costs.

There is some discussion about whether recent record low bids for solar and wind projects, around US$0.02/kWh in a number of countries, are realistic and whether they credibly indicate a continued trends toward lower costs.[i] However, all recent projections of solar and wind expansion have been

i From a systems point of view, integration costs may have to be added to the purchase price to arrive at the true economic cost per kWh. However, there is significant debate over methods to calculate integration costs, and they will be very different depending on the power system in question.

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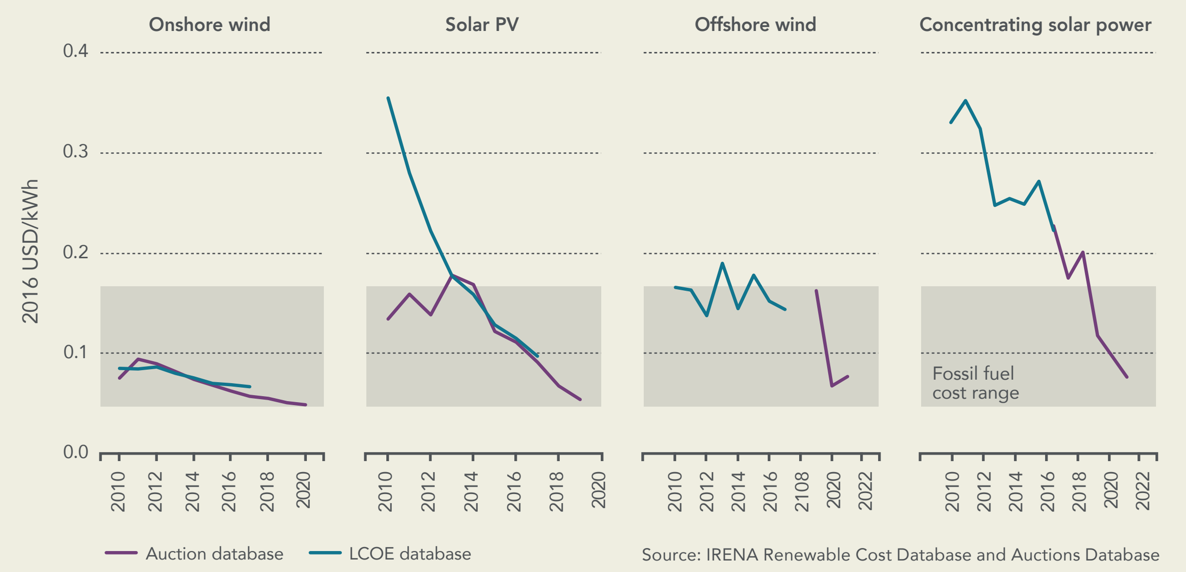
3.1. Costs for wind and solar technologies



3.1. The Levelized Cost of Energy (LCOE) and auction prices (winning bids) for projects already commissioned or contracted to be commissioned, between 2010 and 2022. For the key commercially available solar and wind technologies, average costs are in the process of reaching approximately US$0.05/kWh. This is not only at the lower end of the fossil fuel cost range, it is also equivalent to the average LCOE of hydropower.[2]

too conservative, and some observers expect costs to further decline to approximately US$0.015/kWh, where a floor may be reached[3]. Rapid innovation and fierce competition for market share, both by manufacturers and developers, are expected to continue. Countries that have established auction schemes have seen strong competition and lower costs, and so a proliferation of auction schemes should contribute to continued downward cost trends and more consumers benefiting from even lower power prices.

The main explanation for the impressive drop in cost has been the massive scaling-up of the industry. Furthermore, compared to large civil engineering projects — which commonly have cost overruns and delays owing to their complexity — wind and solar projects benefit from far lower complexity in components and modularity, each of which facilitates scalability of both construction and installation[4].

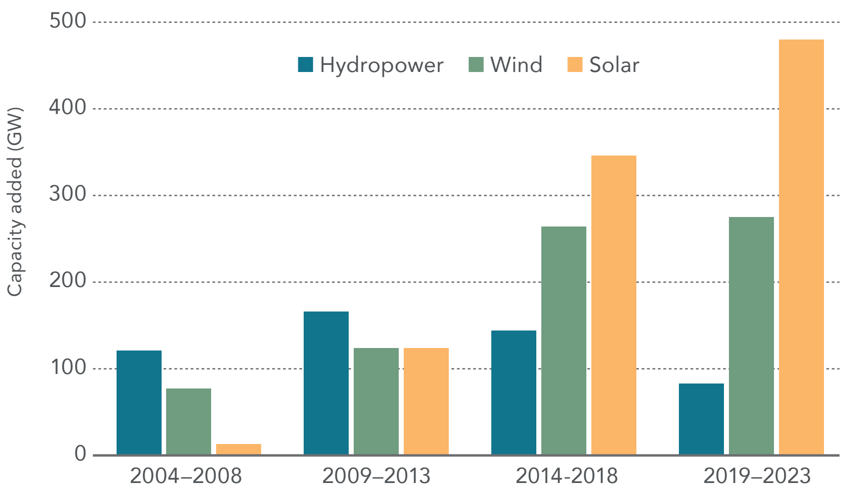
Increasingly, governments are accepting that wind and solar technologies are a viable alternative, and have included them in their national plans, created supportive regulatory frameworks, and made international commitments to promote them, in particular through the Nationally Determined Contributions (NDCs) under the Paris Agreement.

As a consequence, investments in solar and wind have overtaken all other power generation technologies, leading to a rapid expansion of capacity. About 100 GW of solar PV and 50-60 GW of wind were installed globally in 2017, and again in 2018 (much of it in China)[5]. These are large-scale investments, comparable to the entire power generation capacity of large countries like India (350 GW) or Japan (320 GW). Although solar and wind generation were originally associated with distributed, community-scale or off-grid generation — and these applications still have a role to play in accelerating energy access — wind and solar have become a primary choice for utility-scale power plants, capable of supplying major cities and industries. Because of these large additions of wind and solar, renewable sources represented two-thirds of new power generation capacity added globally in 2018.[6]

Behind the rapid expansion of solar and wind are technological advances and economies of scale that have driven down costs to competitive levels, combined with policies that removed barriers and opened markets to these new technologies. Subsidies such as guaranteed feed-in tariffs are no longer necessary in most countries and are being phased out. Léger et al. (2018) modeled the implications of an auctions-as-reality scenario, with recent auction prices instead of average prices for solar and wind, for Mexico, Germany, and India. In this scenario, solar and wind would replace gas and coal much earlier than previously projected, leading to cumulative GHG emissions reductions until 2050 of 15% in Germany, 25% in India, and 30% in Mexico.[8]

The global potential for solar and wind is generally estimated to be on the order of several times the current global power consumption, although in some countries land-use competition, public acceptance, resource quality and remoteness could eventually become constraints[9]. If poorly sited, the significant expansion of wind and solar needed to meet climate objectives could have major impacts on natural habitats and carbon storage[10].

However, Baruch-Mordo et al. (2018) found that most countries have sufficient availability of low-impact wind and/or solar to meet climate commitments and much of their future power demands (reviewed in more detail in Chapter 5)[11]. For example, solar panels can be installed on buildings, over parking lots, on industrial brownfield sites, or floating on reservoirs. Wind farms can be co-located with some types of agriculture or installed in areas with low land values, or offshore in coastal waters where there are fewer competing uses. In addition, to avoid additional power lines and reduce transmission costs, solar and wind facilities can be sited adjacent to existing transmission infrastructure. This kind of smart siting can also reduce cumulative impacts, such as fragmentation of the landscape, and there is now a growing body of knowledge regarding optimization of siting of new solar and wind facilities, taking into account multiple criteria such as the quality of the resource, installation costs, and environmental and social acceptability[12].



3.2. Recent growth in renewables by type

Global renewable power capacity additions, 2004-2023[7] (From IEA 2017)

Hippos in Stiegler's Gorge on the Rufiji river in the Selous Game Reserve, a World Heritage Site in Tanzania. The gorge is the site of a planned hydropower dam.

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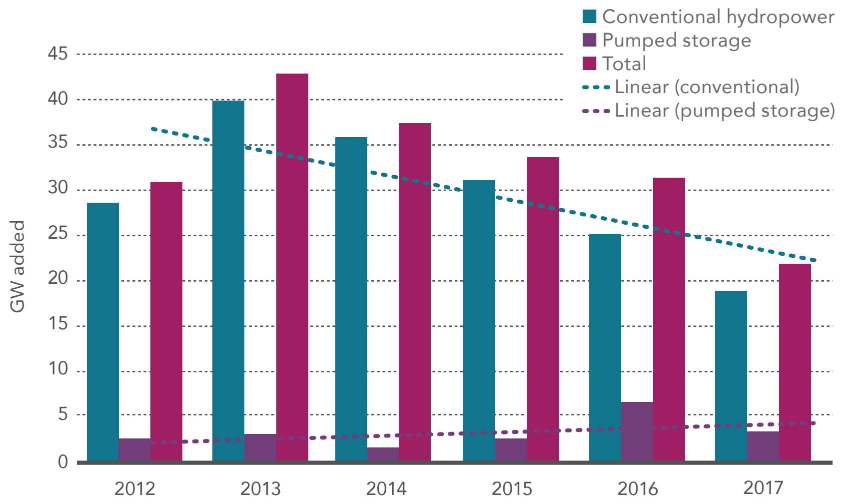
3.1.2 Integrating solar and wind into grids

While cost and potential are unlikely to be major barriers for the continued expansion of solar and wind power, there is a key difference between power generation in solar and wind farms and most other generation facilities. Solar and wind are not continuously available and dispatchable to meet the current power demand. Instead, their generation is intermittent and variable, dependent on the time of day and the weather. They are location-specific, and some areas may experience extended times with minimal or low generation. Although generation can be predicted, such predictions — as well as the predictions for power demand — are never certain, and thus every power system needs to include other technologies besides solar and wind to balance supply and demand in the short term.

At the early stages of solar and wind deployment, intermittency is not a major issue, as the existing power grid can easily accommodate the new generation capacity. For the major regional grids in the United States, around 30% solar and wind grid penetration can be accommodated with minimal system changes[13]. As the share of solar and wind grows, however, system planners and operators are learning what investments in the grid and operational adjustments they need to ensure that balance is maintained. This is not a fundamentally new challenge, as they have always had to manage changing sources, varying loads and the possibility of interruptions in supply or transmission.

There are already a number of countries with high levels of variable renewables, which are all managing intermittency and maintaining stable grids in their own ways. Denmark, for example, with almost 60%



3.3 Hydropower capacity additions

Newly installed hydropower capacity, in GW/Year, 2012-2017[15]

variable renewables, relies on its integration with the large European grid, including hydropower-dominated Norway.

While intermittency may be the main concern with solar and wind generation, there are also other technical issues that need to be resolved. System planners and operators will be concerned with so-called "ancillary power services," such as short-term frequency and voltage regulation, and black start capability (restoring an electric power station or a part of an electric grid to operation after a total or partial shutdown without relying on the external electric power transmission network), which can be provided by different generation and transmission technologies. Hydropower has a strong role to play in providing grid stability.

3.2 TRENDS IN HYDROPOWER

3.2.1 Recent downturn in investment

The scale of hydropower development has risen and fallen several times in its long history. Regionally, construction booms shifted from North America and Europe in the 1950s-1970s to South America and, later, East Asia in the 1990s-2010s. In the past few years, there has been a significant global downturn in hydropower development, largely driven by China nearing the end of its hydropower expansion program, with no corresponding increase in investment elsewhere to offset the decline (Figures 3.2 and 3.3). The most recent data from IRENA show that this trend continued in 2018[14].

These data show the completion of projects and commissioning of new capacity. As such, they reflect past investment decisions, typically 5-10 years ago. Few data are available on current investment decisions or project approvals, which would allow projections for future capacity additions. While simple extrapolations from recent trends should be viewed with caution, there are some indications that investment in conventional hydropower may continue to decline:

- ***High-profile cancellations.*** Recent years have seen multiple projects being suspended and cancelled, some by developers and some by governments. High-profile recent examples — including Myitsone (Myanmar), HidroAysén (Chile), and São Luiz do Tapajós (Brazil) — represent an aggregate of US$1.3 billion in stranded investments and 18 GW of undeveloped capacity[16]. There are currently only a few large projects under construction that will enter operations in coming years[ii].
- ***Policy decisions against hydropower.*** Several countries have drastically reduced the targets for new hydropower investments in their master plans, and political leaders in these countries have signaled that hydropower may no longer be a priority.
- ***Performance in recent auctions.*** Many countries now use auctions or similar competitive market mechanisms to select the lowest-cost generation projects for future supply. Hydropower developers find it increasingly difficult to compete against other types of projects in these auctions. For example, in 2017, hydropower accounted for a combined 33 MW out of 2,085 MW awarded in auctions in Brazil and Argentina, just 1.6% of the total, while in Chile and Mexico, no hydropower was selected through auctions. Most winning bids came from solar and wind projects, with a small number of biomass, geothermal, gas, and other projects[17].
- ***Slowing orders for hydropower equipment such as turbines.*** Equipment manufacturers report relatively low levels of orders, except for pumps[18].

The increased investment in pumps confirms that at least one sub-sector of hydropower appears to be resilient, if not growing — pumped storage, a technology that can facilitate increasing share of variable renewables(Figure 3.3)[19].

3.2.2 Underlying reasons for declining investment

Global economic growth has slowed down considerably in the last 10 years. In combination with a structural shift to service industries and more efficient use of electricity (e.g., in appliances and industrial processes), the pace of growth in power demand is waning. This has led to a slowdown in power generation investments, across all technologies.

More specifically for hydropower, there are a number of reasons why investment is falling:

- ***Water Resource Management Challenges.*** With rising populations and demand for water for a variety of purposes, including environmental and aesthetic purposes, the allocation of water and river reaches to hydropower, and water storage in dams in general, is increasingly being challenged. Global active reservoir capacity has been declining because of the slower addition of new capacity and sedimentation of reservoirs[20]. A contributing factor has been that investment in surface irrigation, which often involves dams, has been in a long-term decline as the most suitable areas have already been developed[21].
- ***Increasing Hydrological Risks.*** Brazil, East Africa, and California are just some examples of regions that keep experiencing droughts, which affect hydropower generation. Depending on the share of hydropower in the generation mix, this can lead to curtailment of power supplies and significant economic losses. The expectation is that such droughts will become more frequent with climate change, and the seasonality of flows will become more pronounced and less predictable. Some basins, such as the Zambezi, are expected to see significant declines in average runoff, average generation and firm generation. Furthermore, the magnitude and frequency of large flood events is expected to increase in many parts of the world, which poses risks for dam safety[22].
- ***Cost and Schedule Overruns.*** It is well documented that hydropower projects globally have significant delivery risks in terms of costs and schedule — larger than for most other power technologies and other infrastructure sectors[23]. Delays translate into reduced financial viability because of increased interest payments during construction, increased payments to contractors to maintain their presence on site, delayed revenues, and in some cases, penalties for not meeting contractual delivery requirements. Delayed power deliveries also carry risks for consumers and economies.
- ***Technical Problems.*** Although hydropower projects have been built for more than a century, significant engineering challenges remain. The recent dam failure at the Xe-Pian Xe-Namnoy project in Laos, which likely killed hundreds of people and displaced thousands more, and large-scale technical difficulties at the 2,400 MW Ituango project in Colombia, illustrate some of these technical challenges. In Bhutan, geological issues have resulted in average costs more than doubling between the DPR stage (detailed project report, the basis for investment decisions) and project completion[24].
- ***Increasing Social Resistance***. Resistance against large infrastructure in lower income countries, including hydropower projects, is primarily due to fears of social disruption, displacement, and inadequate compensation, while in richer countries it is typically linked to environmental concerns, in particular the loss of wilderness areas. Concerns about costs and safety can also play a role. Such controversies are another factor leading to project delays and have contributed to the high-profile suspensions and cancellations mentioned above.
- ***Best Sites Already Taken.*** The increasing difficulties for developers are also related to the fact that, in many regions, the best sites have been developed and the remaining sites are less than ideal. This depends, obviously, on the extent to which regions have developed their potential. Africa has many more good sites left than North America, for example. In Brazil's Amazon, its "last hydropower frontier," government perspectives have now shifted against large dams as there are fewer attractive sites available that would not affect protected areas and indigenous lands and

ii Projects above 1 GW include Baihetan (China, 16 GW), Wudongde (China, 10.2 GW), Grand Renaissance Dam (Ethiopia, 6.45 GW), Rogun (Tajikistan, 3.6 GW), Ituango (Colombia, 2.4 GW), Xayaburi (Laos, 1.285 GW), Site C (Canada, 1.1 GW).

require long transmission lines[25]. China's leaders are coming to similar conclusions, as most of the cascades on major rivers such as the Yangtze and Lancang are nearing completion.

- ***Increasing Hydropower Costs.*** While costs for wind and solar have been declining, average hydropower costs have been gradually increasing over the past decade. Between 2010 and 2017, average total installed cost increased from 1,171 to 1,535 US$/kw and LCOE increased from US$0.04/kWh to US$0.05/kWh, with costs spread over a fairly wide range[26]. The shift to less ideal sites and general inflation in the construction sector are two of the key factors behind these rising costs.

3.2.3 Sustainable hydropower for the future

The renewable energy landscape is shifting, with new renewables presenting both a challenge and a potential opportunity for hydropower. Certain types of hydropower are becoming less competitive and potentially not necessary. However, low-impact hydropower plants that provide storage capabilities and flexibility could become an important component of the world's transition to deploying considerably more intermittent renewable energies.

Whether there is a specific need or not, such dedicated back-up and energy storage plants will only be built where there are specific markets or specific regulatory requirements for the services they provide, and many countries have not yet created such frameworks, or do not yet have sufficient price differentials between peak and off-peak power. A number of potential pumped storage projects in Europe are currently on hold, for example, as companies are waiting to see how power markets will evolve. In the meantime, alternative storage technologies and other solutions to intermittency may also be reaching levels of maturity and cost-competitiveness that make hydropower unnecessary.

The International Energy Agency (IEA) is concerned that the current low levels of investment in hydropower may not be sufficient for it to fulfill its potential role in facilitating the expansion of variable renewables[27]. Some governments, including India's, are considering ways to subsidize hydropower so it can remain competitive and fulfill that role[28]. Such reforms are made more difficult, however, by mixed public perceptions of the hydropower sector.

Over the last twenty years, the sector — led by the International Hydropower Association (IHA) — has tried to enhance sustainability at the project level, reduce risks, and improve reputation and public acceptance[29]. Some progress has been made but widespread acceptance of best practices by the industry has been slow and this has contributed to continuing conflicts and rising costs. Opposition to hydropower development has become quite entrenched in a number of countries.

There are also inherent limitations to improvements at the project level. For hydropower to have a sustainable future in the renewable revolution, it can only be managed effectively at a system level. Various tools and methods exist to guide better selection of hydropower projects, minimize cumulative impacts, and maximize benefits[30]. While implementation is still at an early stage, and rarely required by governments, there are emerging cases demonstrating the value and opportunity from approaching hydropower planning at the system-scale.

Better still is the opportunity to assess hydropower in conjunction with new renewable deployment. Countries should consider developing new hydropower primarily to complement and support the deployment of low-impact wind and solar. In places where hydropower already exists on a grid, there may be no need to develop additional projects, but instead re-operate or retrofit existing assets. Eventually, while existing plants will remain operational for many years, hydropower capacity will decline as more projects will be decommissioned because of increased awareness of the impacts, reservoir sedimentation, and the high costs of maintaining safe operations.

What is becoming clear is that the vision of low-carbon, reliable, accessible, affordable, and low-impact power systems is increasingly attainable. The remainder of this report will describe pathways to achieve that vision.

The Richard B. Russell Dam on the Savannah River (Georgia, USA) added four 75 MW reversible turbines, allowing it to pump back and store water from the reservoir of the Strom Thurmond Dam, which is backed up to its base.

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Chapter 4

ACHIEVING LOW CARBON, LOW IMPACT GRIDS

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Chapter 4

In this chapter, we explore the technical feasibility of low-carbon, low-cost and low-impact power systems through descriptions of the modeling and planning methods that can be used to design grids. We then summarize modeling studies that illustrate power systems that achieve these three objectives.

KEY POINTS

- **Capacity expansion models can be used to explore the technical and economic feasibility of power systems that are low carbon and low impact.**
- **Using capacity expansion models for Chile and Uganda, we explored scenarios that were low carbon and included protections for specific rivers: free-flowing rivers (Chile) and rivers within national parks (Uganda). The river protection scenarios had either no effect on cost (Uganda) or a very small effect (Chile, 1-2% more expensive) compared to business-as-usual (BAU) scenarios. The low-carbon, low-impact scenarios for Chile had one-quarter of the carbon intensity, with thousands more kilometers of free-flowing rivers remaining compared to the BAU.**
- **A range of best practices can be used to avoid and/or minimize impacts from hydropower, encompassing: (1) rehabilitating and retrofitting existing hydropower dams, re-operating dams and cascades, and adding turbines to non–powered dams; (2) planning for low-impact hydropower development and operation within energy and water-management systems; and (3) design and operation of individual dams.**
- **Blending application of the mitigation hierarchy with regional development planning for new wind and solar projects can reduce impacts and conflicts, improve conservation outcomes, and facilitate faster permitting and development.**

The environmental performance of a power system is partly influenced by grid-scale properties, such as the mix of different generation sources: a grid with a large proportion of coal will have poor performance on greenhouse gases, a grid dominated by hydropower is more likely to have high impacts on rivers. But much about the environmental performance of a power system requires understanding how projects perform within a landscape. For example, where a project is sited has a particularly strong influence on it environmental and social performance. Thus, to round out this examination of how to achieve sustainable power systems, this chapter also reviews best practices for project siting for renewable energy sources, along with best practices for the design and operation for hydropower projects and systems.

Planning a power system that can meet the three sustainability objectives will require an integration of these scales: capacity expansion models to select components of a system, coupled with design and planning processes to guide where and how those components interact with the landscape. This integration could be iterative, such as a capacity expansion process to designate targets for wind, solar and hydropower and then landscape-scale planning processes to guide site selection for the projects that can meet the targets. But both scales are ultimately based on quantifying the tradeoffs of different options — in terms of performance across financial, economic and environmental criteria — and so, ideally, they would be integrated.

4.1 POWER SYSTEMS AND PLANNING FOR A LOW-CARBON, LOW-COST, AND LOW-IMPACT GRID

Power systems need to balance three dimensions that are in tension with each other: cost, reliability, and environmental and social performance. Reliability is a property of the electricity grid that describes the likelihood of being able to satisfy loads at any given time. A more reliable system is typically more expensive to build and operate, since it usually requires redundant infrastructure available in case an outage happens. In terms of cost, power systems have historically kept costs low by generating electricity with cheap fossil fuels, without internalizing pollution costs. As fossil fuel costs fluctuate, and other technologies and strategies have become economically competitive, the selection of an optimal portfolio has become much more challenging. Planners need increasingly sophisticated power system models and processes to assess all the potential combinations, and trade-offs, of existing and new technologies.

Electricity grids are among the most complicated systems that people have invented. The operation of a power system requires an almost instantaneous balance of supply and demand across vast geographical areas that are linked through large transmission and distribution systems (Figure 4.1).

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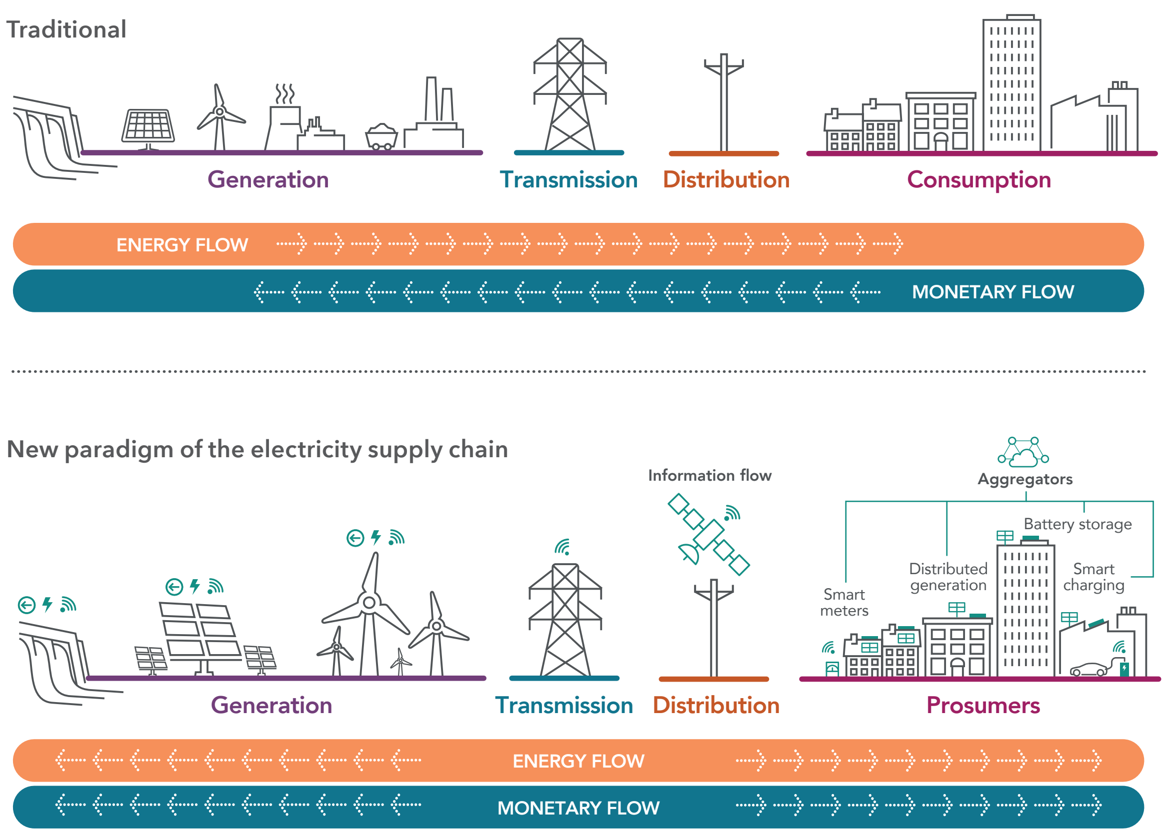
Within a traditional power system, generation units such as fossil fuel plants, hydropower, solar PV, wind, and geothermal power are located far from load centers, usually because of geographic or environmental constraints. Their output is then transported through high-voltage transmission lines that bring electricity close to cities. At that point, voltage is reduced and a local distribution system is utilized to bring power to end-users. This traditional system used to be one-way — from generation to load — but the adoption of distributed energy resources, such as rooftop solar PV, is producing flows in the opposite direction with complex consequences.

The challenge of meeting demand at all times comes from its uncertain temporal variation. At any given second, millions of consumers are turning devices and processes on and off, causing demand to fluctuate. At the same time, generation from variable resources as wind and solar is also changing rapidly. The system has to adapt quickly

4.1. Electricity supply chains



4.1. Traditional and new paradigms for electricity supply chains. (adapted from IRENA, 2019)[1]

to these changes to perform at desired levels of reliability. These adaptive actions are called ancillary services, which can be provided by adjustable generators — such as hydropower, but not solar PV — or more recently by load that can be disconnected on a real-time basis.

As power systems grew more complex, long-term planning processes were developed to grapple with reliability requirements. Most recently, the demand for climate change mitigation has led to complex policy questions around decarbonizing the system: what technologies should be used, and when and where should they be deployed? Planners developed forward-looking models that had several components:

- A set of load forecasts that represent policy-relevant scenarios of how residential, commercial, industrial, and transportation consumers would grow.
- A portfolio of existing resources and potential technologies, including supply and demand side.
- Scenario analysis or other forms of exploring the evolution of the system under varying assumptions of cost, prices, policies, and technological progress.
- A basic representation of the generation and transmission-distribution system, including operational and investment decisions subject to meeting certain levels of reliability, emissions, impact, and others.

There are two particular dimensions that long-term planning power systems models should represent adequately:

1. ***Time:*** Planning models for sustainable grids should reflect the challenges of hourly balancing of the system, but also account for long temporal scales that describe the evolution of the system over several decades. In addition, it is important to capture the natural synergies of resources and load. For example, solar PV generation is typically coincident with demand for air conditioning.
2. ***Space:*** These models should also explicitly reflect the spatial properties of the resources and the load, and the associated transmission requirements.

Adequate time and space representations are especially relevant for holistic system-level analysis of hydropower resources.

1. ***Time:*** Hydropower plays an important role in power systems because it can rapidly adjust its output to compensate for variations in load or from variable generation, such as wind and solar power, often within minutes. Hydropower output can exhibit substantial monthly variations between wet and dry seasons, particularly for smaller reservoirs and run-of-river projects. Finally, hydrological cycles affect production in the long term, with the extreme case of drought severely curtailing performance.
2. ***Space***: Each hydropower project has context-specific impacts and therefore should be represented at the project-level rather than aggregated. At the same time, a system-level analysis requires identifying the river and basin where a hydropower project is located.

There are several models and planning exercises that demonstrate that sustainable grids are technically and economically feasible. Williams et al. (2015) demonstrate that deep decarbonization up to 80% of 1990 GHG emissions for the US economy is technically possible using existing commercial technologies. They find that achieving these levels by 2050 would cost less than 1% of GDP[2]. A study of the Western US show that decarbonization of the power sector to half of 1990 levels can be achieved with existing technologies with less than a 20% increase in system costs. Researchers have proved that renewable energy-based systems can reliably supply a power system for 99.9% of the time, and another study even suggested 100% renewable pathways for around 140 countries[3].

At a more granular level, the Renewable and Appropriate Energy Laboratory (RAEL) at the University of California, Berkeley, has demonstrated the feasibility of sustainable and affordable pathways for power systems in several regions. For Sarawak in Malaysia, RAEL found that a suite of decentralized strategies based on clean technologies would avoid the need for a large dam, which would have displaced indigenous communities (Box 4.1)[4]. For Kosovo, alternative clean energy pathways were

BOX 4.1

SARAWAK

In Malaysia, the state government of Sarawak is implementing a development program called the Sarawak Corridor of Renewable Energy (SCORE) with a predominant emphasis on hydropower.

At least two coal power plants and 12 large hydroelectric dams, with projected total generation equivalent to 8 times required demand, were scheduled to be built before 2030. However, full development of these projects would cause significant social and environmental impacts, including the displacement of approximately 100,000 indigenous people and the loss of at least 2,425 square kilometers of direct forest cover.

Researchers at RAEL adapted a long-term energy simulation and analysis tool and demonstrated its use in comparing energy options in Sarawak. Results for medium- and high-demand growth rates show that 2030 demand can be fully met and generally exceeded with existing and under-construction dams (Bakun and Murum). Alternative scenarios show that decentralized generation sources, including PV and biomass, could be combined to meet future demand. Under lower future renewable resource costs, the system could be primarily based on biomass and solar PV, with no conventional generation required.

In 2015, the government announced a moratorium on the Baram Dam, largely in response to local and international pressure. On March 21, 2016 a legal decision to solidify this position was announced: the Government of Sarawak reaffirmed indigenous ownership of the land for the dam site, reversing a previous classification that would have allowed the development to proceed. This decision demonstrated that communities can advocate effectively to protect their interests and that science communication can play a substantial role in supporting these advocacy efforts.

more affordable and much more sustainable than a projected coal plant[5]. For Laos, large-scale hydropower development had a higher risk of cost overruns while renewable technologies such as solar were able to meet projected demand (both domestic and export) at a lower total cost of investment (see more details in Section 7.4)[6].

Researchers at RAEL have also developed extensive analyses for sustainable and affordable power system pathways for the Western US, Chile, Nicaragua, Kenya, China, and Uganda employing the SWITCH model (see Box 4.2). In this report, the SWITCH model was used to explore in more depth low impact hydropower and low-carbon pathways for two of these regions: Chile and Uganda.

MODELING RESULTS FOR CHILE AND UGANDA

In the analyses for both Uganda and Chile, reference scenarios (reported as "business-as-usual" or BAU) are built using the original assumptions for each model[7]. The analysis period runs from 2025 to 2045 in the case of Chile and from 2020 to 2045 in the case of Uganda.

BOX 4.2

THE SWITCH LONG-TERM PLANNING MODEL

The SWITCH model was developed and is maintained by the Renewable and Appropriate Energy Laboratory (RAEL) at the University of California, Berkeley.

SWITCH is an algorithm that estimates the least-cost investment decisions to expand a power system subject to meeting load forecast and a host of operational constraints. The model concurrently optimizes installation and operation of generation units, transmission lines, storage, and the distribution system, while meeting realistic operational and policy constraints. SWITCH employs very high spatial and temporal resolution for each region analyzed, allowing for an improved representation of variable resources like wind, solar, and storage.

For Chile, we ran two scenarios to compare with BAU to explore how protecting free-flowing rivers (FFR; see Box 2.1)[8] would affect expansion of the power system. Neither of these two scenarios allowed additional coal generation and they included constraints on hydropower based on the potential policy goal of maintaining FFRs.

1. ***Basin-constrained scenario ("basin")*** does not allow new projects within undeveloped basins (i.e., it only allows new hydropower to be developed in basins with current operational projects: about 35% of potential hydropower plants remain eligible).
2. ***Free-flowing river-constrained scenario ("FFR")*** does not allow new projects on rivers that meet the criteria for being free-flowing (about 15% of reference hydropower plants remain eligible).

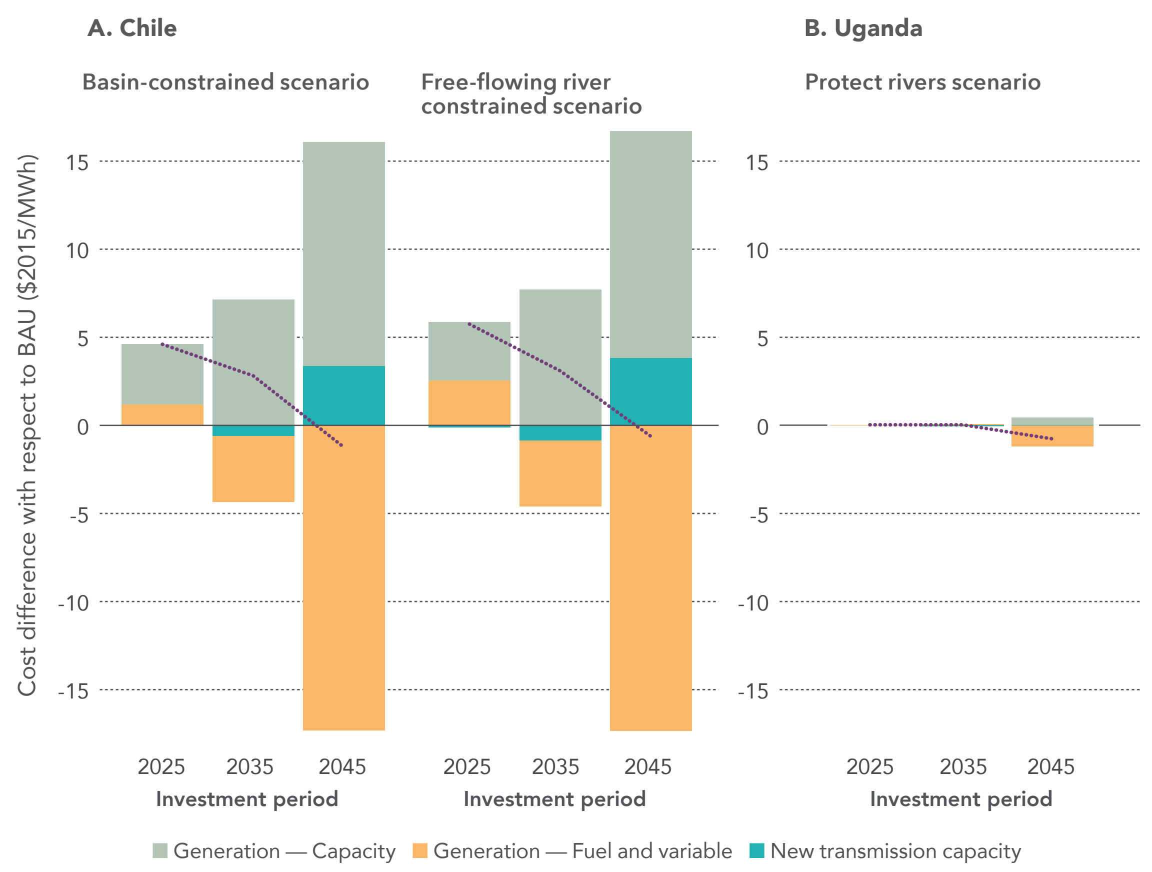
For Uganda, we ran one scenario to explore how a policy that protects rivers within protected areas from hydropower development would affect expansion of the power system. The BAU had selected two projects on the Victoria Nile from the portfolio of potential hydropower sites, both of which are located within Murcheson Falls National Park. A "protected area" scenario removed these two sites as options.

Throughout the rest of the results section, we refer to the non-BAU scenarios collectively as low-carbon, low-impact or LCLI when necessary. Note that here we are using "low impact" as shorthand for "increasing protection for, and reducing impacts on, rivers" acknowledging that nearly all energy projects have some impacts.

Costs

For both regions, the scenarios that limited hydropower to protect either free-flowing rivers or national parks are only 0% to 2% more expensive than the reference scenarios, based on Net Present Value (NPV). We report the cost difference between the reference scenario and each of the LCLI scenarios by specific cost categories (generation capacity, fuel costs, and transmission costs). We also report the net cost for easier interpretation (see black line in Figure 4.2). In the case of Chile, the two LCLI scenarios yield very similar cost increase profiles (see Figure 4.2.A). Costs for the "basin" scenario are 1.5% higher than the reference scenario, by about US$1.6/MWh. Costs for the "FFR" scenario are 2.1% higher than the reference, by about $2.2/MWh.

4.2. Cost difference



A. Cost difference between low-carbon, low-impact scenarios and the reference scenario, by period and cost type, for Chile.

B. Cost difference between a scenario that protects rivers in national parks and the reference scenario, by period and cost type, for Uganda.

In the case of Uganda, the "protected area" scenario has nearly equivalent costs as the reference scenario (Figure 4.2B).

The cost structure change between the LCLI scenarios and the reference scenario for Chile is dominated by reduced expenditure in fuel and variable costs, and increased expenditure in capital. This reallocation of expenditures can have important macroeconomic consequences, as reduced purchases of imported fuels affects exchange rates, makes the region less exposed to fuel-price volatility, and increases energy security.

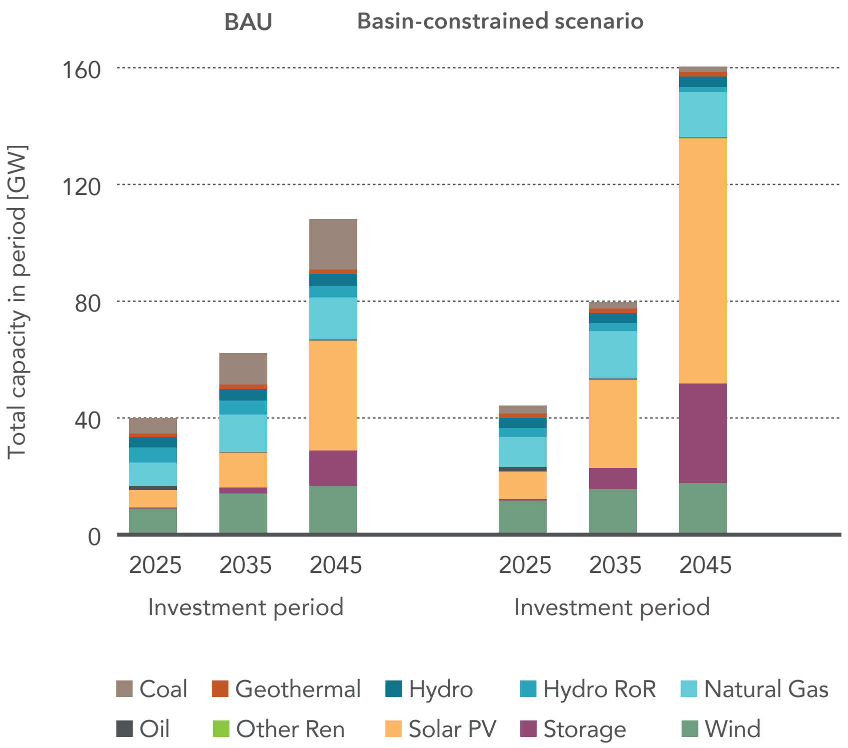
Investment decisions

Capacity deployment decisions describe the evolution of low-carbon and low-impact power systems. Figures 4.3 and 4.4 show the evolution of the power system technology mix for Chile and Uganda, respectively, for the reference and LCLI scenarios. In both countries there is a common pattern for the LCLI pathways: solar PV and energy storage can substitute for almost all of the non-deployed hydropower.

The reference or BAU scenario for Chile includes a substantial expansion of coal power from 4 GW in the first period to over 17 GW by 2045 (Figure 4.3). Hydropower has a much slower expansion, increasing by around 35% during the analysis period. Natural gas-based generation increases threefold, in part due to its role in integrating renewable resources. Despite the fossil fuel expansion, the carbon intensity of the system remains relatively stable at 0.3 tCO2/MWh, although it does double on a per capita basis (Table 4.1).

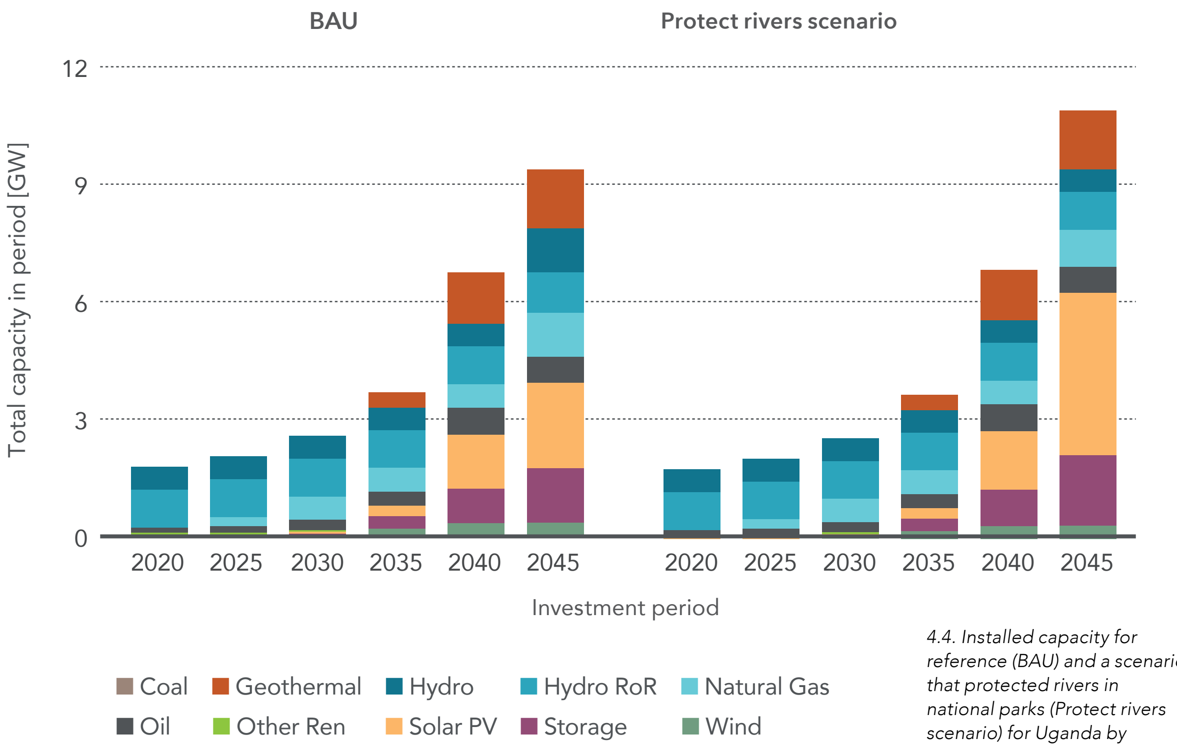
For the LCLI scenarios, by 2025, the model deploys a combination of natural gas, solar PV, and wind power

4.3. Installed capacity – Chile



4.3. Installed capacity for reference (BAU) and a scenario that avoided new dams in undeveloped basins (basin-constrained scenario) for Chile by period and technology

4.4. Installed capacity – Uganda



4.4. Installed capacity for reference (BAU) and a scenario that protected rivers in national parks (Protect rivers scenario) for Uganda by period and technology

to substitute for hydropower and coal. However, by 2045 about two thirds of installed capacity is solar PV in both LCLI scenarios, compared to one third in the reference scenario, with renewables reaching 84% of generation. Carbon intensity for both LCLI scenarios are one-quarter of that of the BAU (Table 4.1). In the same period, there is roughly three times more energy storage deployed in the LCLI scenarios compared to the reference scenario. This highlights the relevance of relying on a suite of different technologies for sustainable growth, sequencing them as they become commercially and technically available.

The reference scenario for Uganda has a very low carbon intensity (<0.05 tCO_2/MWh) and includes expansion of hydropower towards the final period, reaching a total of 2.1 GW from an initial 1.5 GW. Geothermal power and natural gas expansion also play a significant role, reaching over 1.5 GW and 1 GW by 2045, respectively. In the "protected area" scenario, solar PV and storage replace the two hydropower plants within the national park that are installed in the reference scenario (Figure 4.4).

Figure 4.5 shows rivers and hydropower projects in southern Chile, including those that meet the criteria for being free-flowing, those that are already affected by existing dams (non-FFR rivers) and those that become affected by new dams in the various scenarios (and become non-FFR). Directing hydropower away from undeveloped rivers reduces the impacts on FFR in Chile. Under the BAU, 58 free-flowing rivers, totaling 3,850 km, are dammed and no longer meet the criteria for being free-flowing, whereas the "basin" scenario has about half of that level of impact in terms of kilometers (1,960 km) with 14 rivers no longer meeting the criteria for being free-flowing. By design, the "FFR" scenario has no impacts on FFR (note, however, that some impacts will occur on the non-FFR rivers where new projects are built).

In Chile, protecting rivers and restricting new projects to those affecting basins or rivers that have already been developed and fragmented leads to a different set of projects being selected compared to the reference scenario. This process reveals that even with protective policies, there remains a portfolio of hydropower projects that can still be cost-effectively developed. Most of the projects selected in the LCLI scenarios are also developed in the reference scenario, which means that the cost impact of these river protection constraints is very small. While in this analysis we used very simple rules (e.g., no dams on FFR), in an actual application more-comprehensive approaches could be used to compare the tradeoffs and performance of different options to optimize between river protection and power objectives (see Section 4.2).

In Uganda, the results indicate that avoiding building new hydropower projects in a national park has essentially no influence on the costs of the power system.

4.2 HYDROPOWER WITHIN A SUSTAINABLE GRID

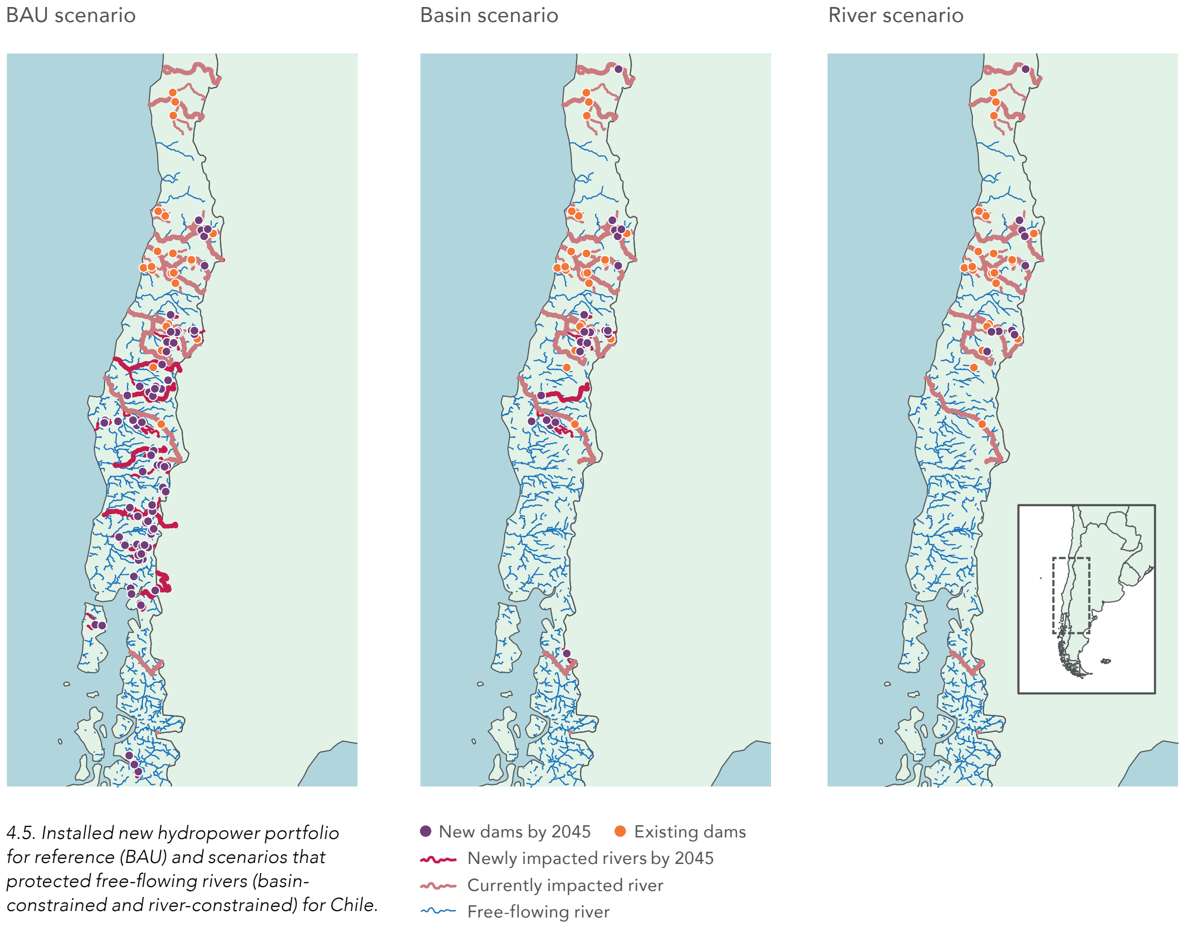
Hydropower is a dominant current source of electricity for many countries and, for grids undergoing expansion, is one of the options that can provide the energy services needed to enable an increasing share of variable renewable sources within a grid. Decisions

Table 4.1

Capacity, generation, and carbon intensity of the various scenarios for Chile and Uganda.

Chile				Uganda	
	BAU	Basin-constrained	River-constrained	BAU	"protected areas"
Total generation by 2045					
Capacity (GW)	108	160.4	161.8	9.4	10.9
Production (TWh)	344	374.2	375.1	15.5	15.5
Total renewable energy by 2045					
Capacity (MW)	64	108.8	109.6	6.2	7.5
Production (TWh)	198	313.8	314.7	14.5	14.5
Renewables share of total production (%)	58%	84%	84%	94%	94%
Total hydropower generation by 2045 (TWh)	35	22.6	19.1	6.1	4.6
Carbon intensity by 2045 (kgCO2/MWh)	0.305	0.075	0.075	0.039	0.036
Emissions per capita (kgCO2/person)	4.86	1.30	1.30	0.01	0.01

4.5. Free-flowing rivers in Chile under different development scenarios



4.5. Installed new hydropower portfolio for reference (BAU) and scenarios that protected free-flowing rivers (basin-constrained and river-constrained) for Chile.

about hydropower's role in a grid, compared to other technologies, will depend on a range of factors, including cost, resource availability, GHG emissions, and social and environmental impacts. Thus, more detailed information on the environmental performance of hydropower in a given region, encompassing impacts, mitigation options and other factors, is needed to inform this decision about the appropriate mix of generation and/or storage technologies. Similarly, if hydropower is selected as a needed component for a grid, then planners and resource managers can strive to minimize the impacts of hydropower development through careful siting, design, and operation. The best practices for minimizing the impacts from new hydropower overlap with those for maximizing the environmental performance of existing hydropower.

Best practice for siting, design and operation of hydropower projects and systems are covered in greater detail in a range of sources[9] and here we briefly cover the following topics:

- Maximizing generation and energy services from existing infrastructure, including upgrading or retrofitting equipment in existing hydropower dams and adding turbines to non-powered dams and other infrastructure;
- Within energy and water-management systems, planning for hydropower to achieve multiple objectives and avoid significant environmental and social conflicts, through analyses to guide the siting and design of new dams and operation of new and existing dams; and
- Best practices for existing dams, including environmental flows and fish passage.

4.2.1 Maximize generation from existing infrastructure

Many regions of the world have mature infrastructure systems, which may provide significant opportunity to add hydropower generation without building new dams. There are several means to accomplish this.

Rehabilitating, retrofitting, or rebuilding existing hydropower dams. Retrofitting older hydropower dams with modern equipment can increase generation from 10-30% and such a retrofit is generally financially beneficial with an efficiency improvement of 4-8%. Retrofits are generally applied to dams that have been in service for 30 years or longer[10]. For example, during the 1980s and 1990s, the Tennessee Valley Authority in the United States was able to increase generation by 34% from its system by modernizing turbines at its dams, while during a similar period, generation declined by 16% from hydropower plants operated by the US Army Corps of Engineers, largely due to aging equipment[11]. These numbers and examples describe projects in which turbines were replaced with units with the same capacity—and used the same civil works and water flow. In some situations, it makes financial sense to retrofit or rebuild the dam, and the rebuilt power plant can have greater capacity than the original. For example, the original 26 MW Rheinfelden project on the Rhine River in Switzerland, built in the early 20th century, was replaced in 2011 by a new 100 MW project that will triple annual generation up to 600,000 MWh[12]. In the appropriate situation, a conventional hydropower dam can be retrofitted with reversible "pumpback" turbines to allow it to function as a pumped storage project. One example is the 1992 retrofit of Richard B. Russell Dam in the United States, which added four 75 MW reversible turbines, allowing it to pump back and store water from the reservoir of the Strom Thurmond Dam, which is backed up to its base[13].

Adding turbines to non-powered dams. Only a relatively small percentage of the world's dams are equipped to produce hydropower. In the United States, 80,000 dams, or more than 90% of all dams in the country, do not produce hydropower. A study by the US Department of Energy found that hydropower was technically feasible on 50,000 of these. This would add 12 GW of hydropower capacity — a 15 percent increase on the country's conventional hydropower fleet. Nearly 70% of this potential increased capacity could be added at the 100 largest identified sites, primarily locks and dams on major rivers operated by the US Army Corps of Engineers[14]. Some projects of this type have already been completed with turbines added to locks and dams on the Ohio River bringing more than 300 MW of capacity to the grid[15].

Drawing on a global database of existing dams, Baruch-Mordo et al., (2018) used conservative assumptions to estimate that upgrades to older hydropower dams could add an additional 134 TWh/year to global electricity generation without any new structures in rivers[16]. Using the same methods, but with higher estimates for efficiency gains from modernization (based on the studies described above), indicates a technical potential of 402 TWh/year from retrofitting older dams. This level of generation is just over 10% of current global annual hydropower generation (approximately 4,000 TWh/year), illustrating the potential contribution that could be made by increasing generation from existing infrastructure.

Beyond increasing generation, the original designs and operating rules of existing hydropower facilities can be reassessed to see if they can be used in a more flexible manner to back up variable renewables. This can involve simply changing operating rules for a single reservoir, improving coordination between projects in a cascade, investing in infrastructure such as increasing storage capacity (by raising a dam), generating capacity (by building a second powerhouse), or installing pumping capacity between two projects in a cascade. Such changes can be highly cost-efficient and low impact, compared to greenfield projects.

4.2.2 Planning for new hydropower

Energy planning exercises could lead to demands for additional hydropower generation. The question then becomes where and how — specifically which sites, designs and operations — would meet energy demands while conserving as much river and environmental benefits as possible. Different hydropower options could include run-of-river vs. storage designs, different capacities, and different reservoir operating rules that determine water r eleases at different times of the year.

While some countries, such as Brazil, have generally planned hydropower at the system scale, hydropower dams in much of the world are usually planned and built on a project-by-project basis, while Environmental Impact Assessments are also carried out at the level of single projects. This scale of planning and review overlooks the cumulative impacts of multiple projects as well as potential synergies between investments planned in coordination.

The potential benefits of a system-scale approach to deliver improved outcomes for both energy and environmental resources are illustrated by recent research in the Mekong basin. For example, Schmitt et al. (2017) found that the current (largely unplanned) portfolio of dams in the 3S Basin (a tributary to the

Mekong) generates 16,000 GWh/year while reducing export of river-transported sand from the basin by 90%. However, had the 3S basin been planned as a system with the goal of maintaining as much sand as possible (vital for the downstream delta), a planned portfolio of dams could have produced the same annual generation but with only a roughly 15% loss of sand[17]. See Box 7.2 for other examples of missed opportunities for more balanced outcomes from the common failure to plan at the system scale.

A range of existing approaches can be used to move planning to the system scale. As mentioned above, some countries have traditionally engaged in energy system planning and/or river basin planning, although these have often given limited consideration to environmental and social values. Environmental review methods, such as Strategic Environmental Assessment and Cumulative Impact Assessment, which are being used increasingly, move the scale of environmental review and guidance on project site selection towards the system scale. Conservation organizations have promoted the benefits of various approaches to system-scale planning, such as The Nature Conservancy's Hydropower by Design[18].

While the 3S example above highlighted the benefits of system planning when seeking better outcomes from two objectives (generation and sediment), system planning will often be required to balance a much broader range of objectives. To address this complexity, river basin simulation models and multi-objective trade-off analysis can be used to compare the performance of many different development and management options across a range of performance criteria, spanning economic, social and environmental objectives[19]. In this approach, the river basin is simulated so that different groupings of hydropower assets (their spatial configuration, size and operating procedures) can be considered in an integrated manner. This means cumulative impacts are evaluated and system-scale strategic outcomes can be assessed before making investment decisions, and can influence siting, design, and operational decisions.

In multi-objective trade-off analysis, a simulation model of the proposed system is connected to a search algorithm to systematically assess the different combinations of options and identify subsets ("portfolios") of options that work well together, given a series of metrics of performance. Because the approach is multi-criteria, it does not identify a single best design, but rather it identifies different combinations of options that best suit different preferences. The search process identifies packages of river basin portfolios (specific combinations of project sites, designs, and operations), which maximize different combinations of stakeholder-defined performance metrics. Examples can be found in Opperman et al. (2017) or in the publications cited above.

Ideally, system planning should move beyond a technical exercise and include extensive stakeholder engagement, both to better understand the objectives that should be considered and to ensure that results feed into meaningful dialogue and decision making. To facilitate this engagement, trade-off plots can be generated and used in interactive settings to allow decision makers or stakeholders to visualize the trade-offs of different options and collectively explore options that may be acceptable to different interests.

An example of a trade-off plot that can be used in an interactive setting is the multi-criteria "parallel axis plot" (Figure 4.6) showing options for river basin development and management on the Tana River (Kenya)[20]. Each horizontal line represents a package of different hydropower and irrigation development and management options. The point at which each line crosses an axis indicates how the corresponding portfolio performs against a given metric. In this example, the metrics are, from left to right, flow regime alteration (an indicator of environmental performance), irrigation revenue and total hydropower generation (axes are oriented so that better performance is always higher).

The plot shows roughly 50 portfolios selected by the search algorithm as being Pareto optimal (i.e., one metric couldn't be improved further without diminishing another metric). The plot reveals how the portfolios vary in terms of performance across the three metrics, and these results can be used to examine tradeoffs and to search for portfolios that may be acceptable to various stakeholders. For example, the top plot has been adjusted to restrict the portfolios that perform well for both flow regime (on the left) and hydropower (on the right). Thick gray bars on the axes indicate the selected acceptable ranges, and portfolios that meet the selected ranges for both are highlighted in dark blue. The results show that none of these portfolios performs highly for irrigation, revealing the tradeoff between objectives. These plots can also be used to search for portfolios that may be acceptable for all objectives (not "win-win" but "close-to-win, close-to-win"). For example, if the acceptable ranges for both flow alteration and hydropower are expanded somewhat (see larger gray bars in lower plot), the subsequent result identifies one portfolio that has higher performance for irrigation — double the irrigation revenue of the highest performing portfolio with somewhat more restricted ranges for the other two objectives (upper plot).

This example shows how multi-objective trade-off analyses can inform system planning, which strives to find development and management options that work well across multiple objectives, such as generation and river protection. Although applied above to a river basin system, the approach can be used to consider portfolios of interdependent energy and water options at the regional or country scale[21].

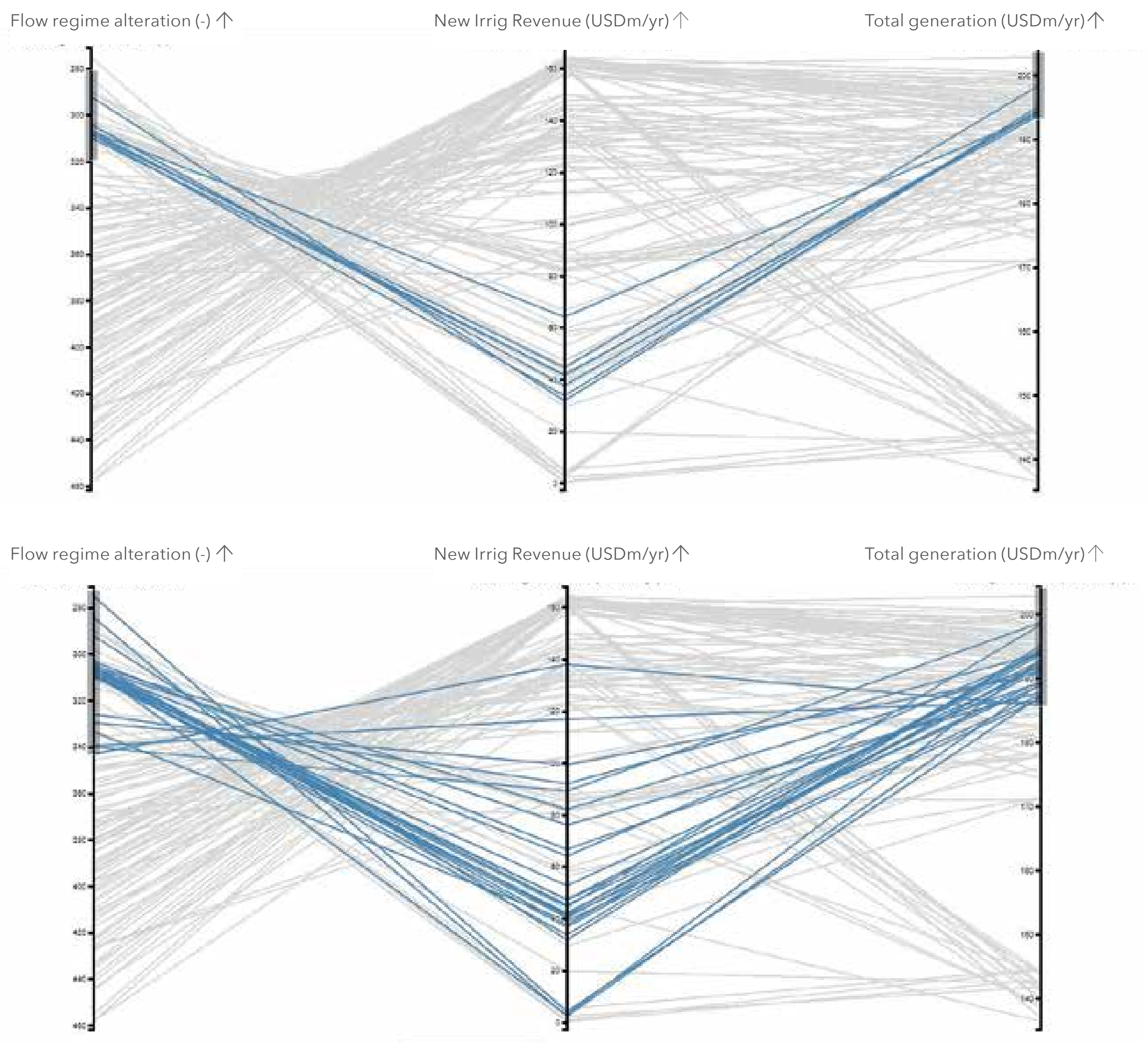
4.6. Interactive parallel axis plots for a multi-objective trade-off analysis. Each line represents a package of hydropower and irrigation development options in Kenya's Tana River basin. The three vertical axes plot the performance against three performance metrics (flow alteration, irrigation revenue, and hydropower generation, from left to right). Preferred performance is towards the top. These plots were generated by polyvis.org and can be explored online at: http://wiseup.polyvis.org/.

4.2.3 Best practices for dam design and operations: environmental flows and fish passage

Dam operations can cause an alteration of a river's flow patterns, which can contribute to negative social and environmental impacts downstream. Thus, managing dam operations to reduce negative impacts or restore important processes is an important part of best practices for hydropower (and thus are among the options that can be assessed within system-scale planning and tradeoff analyses).

There is an extensive literature on methods to define environmental flows to achieve environmental and social objectives through dam operations[22] and a growing set of research papers and case studies on

4.6. Examples of visuals that can be used in interactive settings to guide hydropower planning



the results of environmental flow implementation[23]. For example, hydropower dam operations were adjusted to improve spawning habitat for salmon in the Skagit River in the United States, resulting in a significant increase in successful spawning. Beginning in 2011, the Three Gorges Dam on China's Yangtze River has released a managed flood pulse in late spring intended to promote spawning conditions for native carp species[24].

The interaction between hydropower and variable renewable sources highlights a specific challenge for balancing renewable energy generation with healthy rivers. Throughout this report we discuss how hydropower can help balance grids and facilitate a greater share of wind and solar generation. But for a conventional hydropower dam, providing this balancing role will generally require fluctuations, often rapid[25], in flow releases as the dam quickly responds to changes in wind or solar generation. These rapid changes in operations result in significant fluctuations in discharge and water levels in the river downstream. In extreme cases, these changes pose a danger to human life and property. But even if maintained within levels generally safe for people, these rapid changes in flow are associated with a range of impacts on river ecosystems, including bank erosion and the flushing of fish and other organisms downstream (during a rapid rise in flow) and stranding of fish in portions of the channel that become isolated or dry (during a rapid decrease in flow)[26].

Restrictions on how quickly flows can increase or decrease ("ramping rates") can reduce some of these impacts. Beyond managing ramping rates, there are two primary ways for hydropower systems to provide the service of balancing grids while minimizing, or completely avoiding, these types of impacts on rivers:

- ***Pumped storage.*** Reservoirs with pumpback turbines will release highly variable flows into a downstream reservoir rather than into a river. Similarly, off-channel pumped storage projects also release their variable flow patterns into a reservoir. New innovative ideas are being explored for pumped storage that don't involve a river at all, including (1) seawater pumped storage, using the ocean as an essentially infinite lower reservoir with an existing example in Japan[27] and a proposed project in Chile; and (2) converting abandoned mines and quarries into reservoirs, such as a German coal mine that is becoming a 200 MW pumped storage plant, with similar ideas being explored in the United State[28].
- ***Reregulation reservoirs.*** The most downstream dam in a cascade can be operated to smooth out the fluctuations in flow arriving from the operations of dams further upstream, thus potentially releasing a more natural hydrograph into the river below the cascade. In some cases, a reregulation dam can be built for this specific purpose. For example, on Australia's Mitta Mitta River, the Banimboola Reregulation Reservoir was constructed to reduce the fluctuations in flow from the upstream Dartmouth Dam, allowing that dam to meet regulatory requirements for ramping rates and reduce downstream erosion[29]. These reregulation dams can also generate electricity.

In addition to flow alterations, a primary environmental concern for dams is their impact on fish passage. Many dams are simply too high for effective fish passage. Although considerable research funds have been invested recently in studying fish passage through lower dams on tropical rivers (e.g., for the fish passage facilities on the Xayaboury Dam on the Mekong River in Laos), there remains limited evidence that fish passage can be effective for the majority of tropical fish species. Most successful examples — and the bulk of technical knowledge — come from river systems where the target for fish passage are strong-swimming salmonids that can leap. In contrast to a temperate river with fish passage intended for salmonids or a small number of other species, tropical systems, such as the Mekong or Amazon, can have hundreds of migratory fish species that vary greatly in swimming behavior and their ability to use fish passage facilities. Furthermore, the vast amount of biomass that is moving along a river such as the Mekong during a peak migration time can be far greater than standard fish passage designs could manage.

A recent review found that the average upstream passage rate for non-salmonids at fish passage facilities was approximately 20%, although there are almost no studies from rivers such as the Mekong to include in this review[35]. Even assuming a 20%

BOX 4.3

STRATEGIC DAM REMOVAL

The Penobscot River in Maine historically supported the largest runs of Atlantic salmon in the Northeastern United States, along with 11 other species of migratory fish.

But for more than a century, a series of small hydropower dams (average of 7.5 MW per dam), equipped with antiquated fish passage, had dramatically reduced fish populations. In 2005 a deal was reached between the dam owners, the Penobscot Indian Nation, state and federal agencies and conservation organizations, which called for the removal of two dams and improved fish passage at two remaining dams (one passage project was a nature-like fish bypass)[30]. Dam removals and fish bypass construction occurred between 2013 and 2016 and some fish populations have already showed a rapid recovery, with river herring numbers reaching 1.8 million in 2016 – 135 times the number before the dam removals[31].

Meanwhile, the agreement also included new licenses for the remaining dams, which permitted equipment and operational changes. After these changes, total generation from the basin will slightly increase, even after the dam removals.

The Penobscot illustrates the potential for dam removal to greatly improve passage and boost fish populations. While the Penobscot was coupled with a system-scale approach to maintaining generation, the prevalence of obsolete dams in places such as the United States and Europe means that dam removal can often provide significant gains in river health with little or no loss of benefits – in fact the removal can reduce liabilities and risks. The United States has nearly 100,000 dams and the average age of a dam is 60 years. Nearly 16,000 dams are classified as having "high hazard" potential with rapid growth in that designation as many continue to age with minimal or no maintenance. The American Society of Civil Engineers estimates it would cost US$64 billion to bring all dams in the US up to an acceptable safety level[32]. Approximately 1,300 dams have been removed in the US in the past 30 years, a small proportion of the potential pool of candidates[33]. The dam removal movement is also growing now in Europe, with the largest dam removal on the continent so far – the obsolete 36-meter tall Vezins hydropower dam on the Selune River in France – set to commence in 2019.

Strategic methods can be applied to identify which dam removals will provide the most benefits. For example, a modeling study in the Willamette River basin assessed tradeoffs with various removal options from among 150 dams in the basin. They found that removing only 12 dams could reconnect 52 percent of the drainage basin to the ocean – key for migratory fish such as salmon – with a loss of less than 2 percent of the basin's hydropower capacity[34].

Removal of the Glines Canyon Dam on the Elwha River in 2014 (Washington state, USA), two years after removal of the Elwha Dam. These dams had caused a 99 percent reduction in the Elwha's salmon numbers, previously upwards of 400,000 per year across five species of salmon. The combined capacity of the two dams was 28 MW; since dam removal began, Washington State has added nearly 1000 MW of wind power.

passage rate at a dam on the Mekong or Amazon, the fish passage challenge is compounded by the fact that many mainstem rivers have, or are projected to have, multiple dams. Even two sequential dams with a 20% passage rate will reduce by 96% the proportion of original migrating fish that reach an upstream habitat. In addition, dams with large reservoirs with low velocity water pose a nearly insurmountable barrier for the downstream movement of eggs or larval fish, which require a current.

These challenges for up- and downstream fish passage suggest that the installation of fish passage facilities is highly unlikely to result in successful mitigation of dams as barriers in many river systems. This underscores the value of system-scale planning, which strives to minimize fragmentation, as well as the promising potential of the renewable revolution to make possible electricity systems that rely on alternatives to dams on big, mainstem rivers with important migratory fish populations. In mature river basins with aging infrastructure, strategic dam removal can be the best solution for improving fish passage (Box 4.3).

4.3 REGIONAL PLANNING TO MINIMIZE IMPACTS FROM WIND AND SOLAR EXPANSION

Similar to hydropower development, new wind and solar capacity is generally developed at the project scale and without system-scale planning. This approach foregoes opportunities for more balanced outcomes, including the minimization of environmental and social impacts. Furthermore, the conflicts triggered by these impacts risk slowing the pace of renewable energy deployment and thus undermining progress towards climate objectives[36]. Renewable energy development that occurs through regional and integrated planning avoids the risks associated with piecemeal development by inverting the timing and scale at which habitat, wildlife and other societal values are considered[37].

In a regional approach, the potential effects of multiple projects are considered before they have been individually planned and are moving towards implementation. By applying the mitigation hierarchy (e.g., avoid, minimize, mitigate) to large geographic areas and multiple projects, regional planning has the potential to deliver more effective conservation outcomes, reduce regulatory hurdles for industry, and provide cost savings for both conservation and the energy sector. While uptake of regional planning remains limited, there are concrete examples of the successful integration of the mitigation hierarchy with energy planning within a regional approach.

US Solar Energy Zones. The western United States has seen rapid growth in installed solar power capacity catalyzed by policy incentives and available funding. However, this expansion has raised concerns about impacts on wildlife and other natural resources, leading to some challenges with permitting processes and delayed approvals. In 2012, the US Bureau of Land Management (BLM) adopted a landscape approach to accelerate utility-scale solar energy development on public lands, drawing on comprehensive assessments of habitat values carried out by The Nature Conservancy[38]. BLM's plan applies across six states and considers the direct, indirect, and cumulative effects of solar development over a 20-year period. Through this planning process, large areas of the region have been designated as protected from solar development due to their habitat values. However, the plan also established 19 solar energy development zones, facilitating the expansion of renewable energy. This approach has encouraged cross-agency collaboration and reduced project permitting time from an average of 18-24 months down to 10, while also protecting areas of high conservation value[39].

Sage Grouse Core Areas: The greater sage grouse (*Centrocercus urophasianus*) of western North America was considered a candidate species for listing under the US Endangered Species Act (ESA) due to a range of threats, including energy development[40]. When the US Fish and Wildlife Service (USFWS) initially listed the status of sage-grouse as threatened, proponents of renewable energy development feared that conservation protections for the species and its habitat would constrain projects. In response to these and other concerns (e.g., from ranchers), the Sage Grouse Initiative was formed as a collaboration between state and federal agencies, conservation organizations, and ranching communities. The SGI supported regional planning and spatial prioritization to target conservation efforts and balance energy development with habitat protection[41]. To date, the SGI has secured approximately US$750 million in conservation funding for on-the-ground projects across the 11 western states, enhancing habitat on 1,500 private working ranches that span 2 million hectares — an area twice the size of Yellowstone National Park[42]. In addition, state and federal agencies have adopted a plan that will influence activities on more than 57 million acres of public land[43]. In September 2015, the USFWS concluded that these efforts were sufficient to keep the sage-grouse off the endangered species list, thus reducing regulatory hurdles to renewable energy expansion, while also significantly improving conservation of the sage-grouse across millions of hectares of its habitat.

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Chapter 5

GLOBAL BENEFITS FOR RIVERS OF LOW-COST, LOW-CARBON AND LOW-IMPACT POWER SYSTEMS

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Chapter 5

Accelerating the low-carbon, low-cost and low-impact renewable revolution would lead to countries around the world being powered by electricity systems with considerably lower impacts on rivers than *status quo* projections.

KEY POINTS

- **Estimates for additional hydropower development between now and 2050 range widely, from a few hundred GW to more than 1,000 GW. Different levels of future hydropower development, and how they are achieved (with a business-as-usual approach, or with system planning), will result in dramatically different outcomes for rivers and the ecosystems and people that depend on them.**
- **The global technical potential of utility-scale, low-impact wind and solar (on converted lands such as agriculture, degraded land, and rooftops) is 17 times the renewable energy targets that countries have committed to under the Paris Agreement. This should allow most countries to achieve power systems that are low carbon, low cost and low impact.**
- **System planning to achieve the lowest possible impacts is equally beneficial (and necessary) for all renewable technologies, will improve environmental and social outcomes, and reduce risks for communities, developers, and investors.**

This chapter explores the scope of the potential benefit to the world's rivers, which will depend on the scale and nature of future hydropower development.

As described in Section 2.1, projections vary widely of how much hydropower will be developed to meet the 2050 power demand and achieve climate objectives. For example, among 33 scenarios[i] in the IPCC SR 1.5 report that limit global temperatures below a rise of 1.5°C in 2100 with low overshoot, the median projection for global hydropower capacity in 2050 is 1,820 GW, with an interquartile range of 1,700 to 2,400 GW — from a current baseline of approximately 1,200 GW. A recent study from Teske et al. (2019) projected a 2050 level of hydropower capacity of 1,523 GW[1]; seven of the scenarios in the IPCC report projected a comparable, or even lower, level of development.

We drew on a previous analysis by Opperman et al. (2015) to explore the possible impacts on rivers under this range of projected hydropower development[2]. This analysis used a database of global rivers that included 2.8 million km of channel[3] and a database of 3,700 potential future dams compiled by Zarfl et al. (2015) from a range of sources[4]. The dams are classified as:

- ***Under construction*** — 635 dams with a total capacity of 224 GW;
- ***Potential*** — 3,065 dams that are listed at some stage in the planning process, with a total capacity of 500 GW. Because countries vary considerably in their planning processes and documents, these should not be considered certain to move forward, but rather should be considered as an inventory of potential dams. However, the database can be viewed as a sample of how the world could build an additional 500 GW of capacity, beyond existing and under construction dams.

If all the dams in the Zarfl database were built, global hydropower capacity would reach 1,850 GW (1,126 existing in 2015 + 224 GW under construction + 500 GW of potential) — comparable to the median projection among the IPCC 1.5°C scenarios. This would result in an additional 190,000 kilometers of river channel being impacted by fragmentation, indicated by the highest bar in Figure 5.1[5].

i The IPCC report has 90 1.5°C scenarios and we focused on the 44 that achieved "low overshoot" (a shorter period of time, with lower peak temperature, during which global temperature rise exceeds 1.5°C before declining to that level). Among the 44, 11 from the REMIND model were dropped because all had higher estimates for future hydropower than the highest among the other models, including several that achieved highly unrealistic levels.

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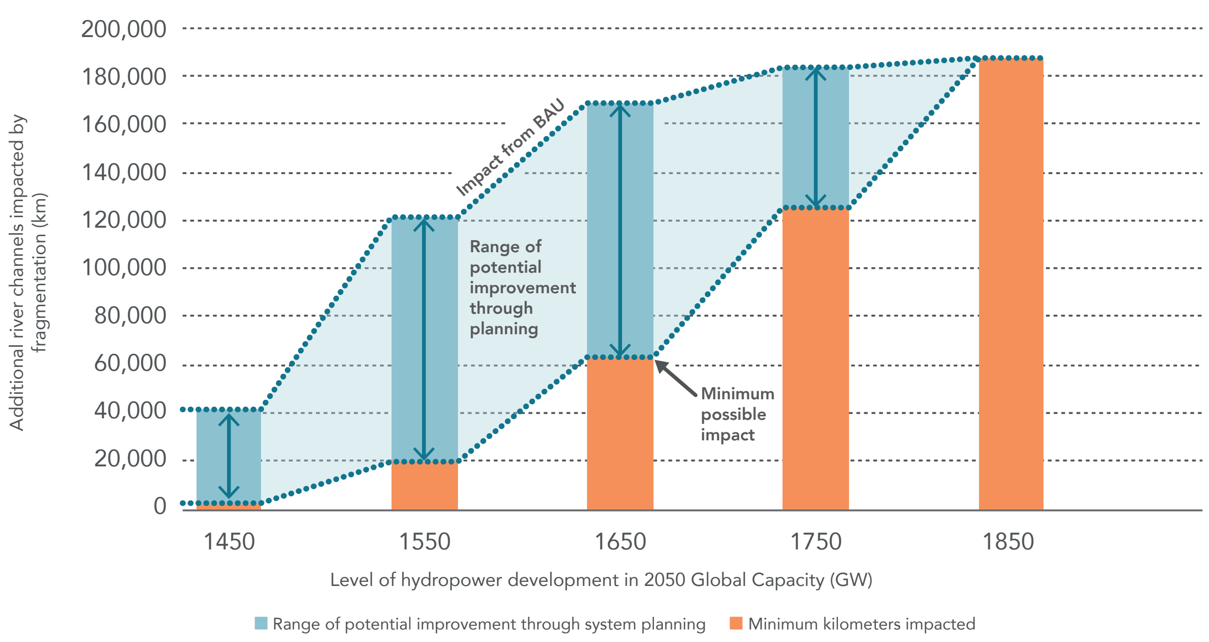
Resources at risk with that level of development include riverine ecosystems and associated fish species, fisheries harvests, and the various resources and services associated with deltas. For example, 70% of the river kilometers that would be impacted at that level of development occur within river basins that are in the top quartile of fish species richness[6]. Similarly, the majority of impacted river kilometers occur within river basins that have the highest fish harvests (Figure 5.2), while many of the most important rivers for flood-recession agriculture are among those that would be most impacted[7]. As described in Chapter 4, high levels of dam development in a river basin can trap large proportions of the sediment (>90% in some rivers) needed to maintain downstream deltas. Several of the rivers with greatest potential expansion of hydropower have deltas with high biological and economic productivity. Among these high-risk deltas is the Mekong and the risk to that delta — and solutions to reduce that risk — are discussed at length in Chapter 7.

Higher levels of development (e.g., approaching the upper quartile of the IPCC scenarios at 2,400 GW) would require thousands of additional dams beyond those in the Zarfl database, and result in considerably higher levels of impact on rivers.

5.1. Hydropower expansion and impact on rivers



5.1. Potential improved outcomes for global rivers through substitution of other technologies for hydropower (moving from right to left) and through system planning to optimize between generation and environmental performance within river basins (blue shaded area within any given level of development). The top of the combined bar represents the level of impact from business-as-usual development of hydropower dams for a given total level of global hydropower capacity by 2050 and the top of the red bar represents the minimum impact possible at that level of development. Note that the bar for 1850 is depicted as having no range of potential improvement from system planning, but that is because that level of development requires building all the dams in the database and thus we can't model different configurations (From Opperman et al. 2015 based on dam database from Zarfl et al. 2015).

However, the trends in cost and levels of investment for hydropower compared to other renewable technologies and the potential to retrofit existing dams and re-operate cascades — along with projections for hydropower in 2050 such as that of Teske et al. (2019) and the lower quartile of the reviewed IPCC 1.5°C scenarios — suggest that future hydropower development may be lower, with associated impacts reduced — and potentially greatly reduced — compared to what is described above.

The reduction of impacts from lower levels of development are shown in Figure 2.1 (note this analysis can't explore impacts from levels of development higher than 1,850 GW because that level exhausts all potential dams in the database). Consider a level of development of 1,750 GW, comparable to the lower quartile of the IPCC scenarios. The top of the red bar represents the minimum kilometers of river impacted by fragmentation at that level of development (e.g., if the system planning described in Chapter 4 was used to minimize impacts on connectivity for that level of development). The top of the blue-shaded section of the bar represents the amount of fragmentation likely to occur with business-as-usual development. Thus, the height of the blue-shaded section of the bar represents the range of potential improvement in outcomes for rivers (reduced fragmentation) possible through system planning.

Comparing the impacts at 1,750 GW with those at 1,550 GW shows two primary ways to reduce impacts on rivers. Even with business-as-usual development, shifting to the lower of these two levels of global hydropower development could reduce impacts by 60,000 km. And then, within that lower level of development, system planning that optimized between generation and river connectivity could reduce impacts by a further 100,000 km – in total, a nearly 90% reduction in impact on river fragmentation. In addition to reducing impacts on rivers, a system-planning approach can reduce social conflicts and thus also reduce investment risks caused by delays and cancellations[8]. These results suggest two main take-home points:

- Lowering total development of new hydropower dams because of greater investment in wind and solar can reduce impacts on rivers at the scale of tens to hundreds of thousands of kilometers globally, depending on how development unfolds within river basins because….
- … System-scale planning can identify spatial configurations of dams that optimize between generation and environmental performance.

The ability to substitute wind and solar for a portion of hydropower development hinges on the improving competitiveness of wind and solar technologies, and the ability of grids to incorporate high levels of wind and solar. But ensuring that this substitution leads to electricity systems that are as low impact as possible depends on the widespread availability of wind and solar power in areas with low impacts on social and environmental resources.

Here, we estimate the potential global pool of low-impact wind and solar in areas where hydropower is projected to expand. For each country, we compare the ratio of potential generation from low-impact wind and solar from Baruch-Mordo et al. (2018) with the generation potential dams in the Zarfl database (see Annex 2). The countries with the greatest projected hydropower development, based on the Zarfl data, represent 75% of all potential hydropower. In each of these countries, the potential generation from low impact wind and solar is an order of magnitude to several orders of magnitude greater than that from potential hydropower (Figure 5.3). This pattern is found in nearly all countries in the world where hydropower expansion is projected (Figure 5.4).

These results do not mean that, in these countries, wind and solar can simply substitute for hydropower. In each region or country, the appropriate mix of generation sources will depend on the characteristics of the existing grid, patterns of resource availability for all types of renewables, and the interactions between grid components (generation, transmission, storage, etc.). The degree to which wind and solar can substitute for a portion of planned hydropower will vary from country to country. Hydropower — including existing projects and strategically planned new projects — can play a key role in facilitating greater proportions of variable renewable sources onto a grid.

However, a primary point illustrated by Figures 5.3 and 5.4 is that, to the extent that wind and solar are becoming an increasingly competitive source of generation, the potential pool for that low-impact resource is large and well distributed. In Chapter 4 we used grid-scale modeling and examples to demonstrate that the renewable revolution is making grids with high proportions of wind and solar, and low impacts on rivers, a reality. If policies and mechanisms can catalyze broader implementation of similar grids, Figure 5.4 indicates that there is extensive potential to do so in a way that minimizes impacts on rivers, land, and people.

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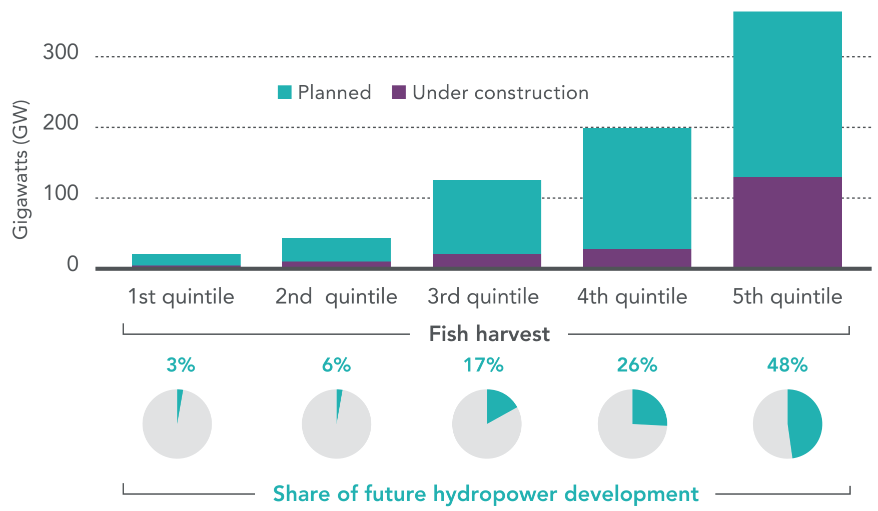
5.2. Potential hydropower expansion and fisheries

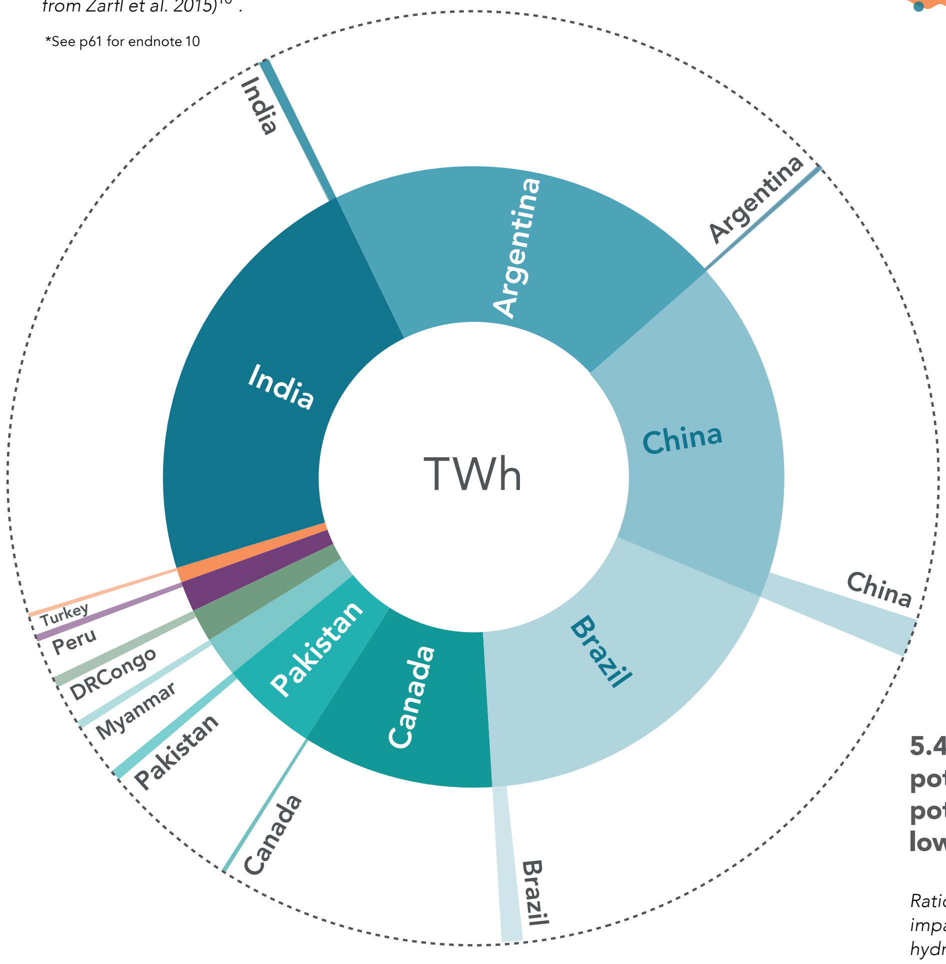


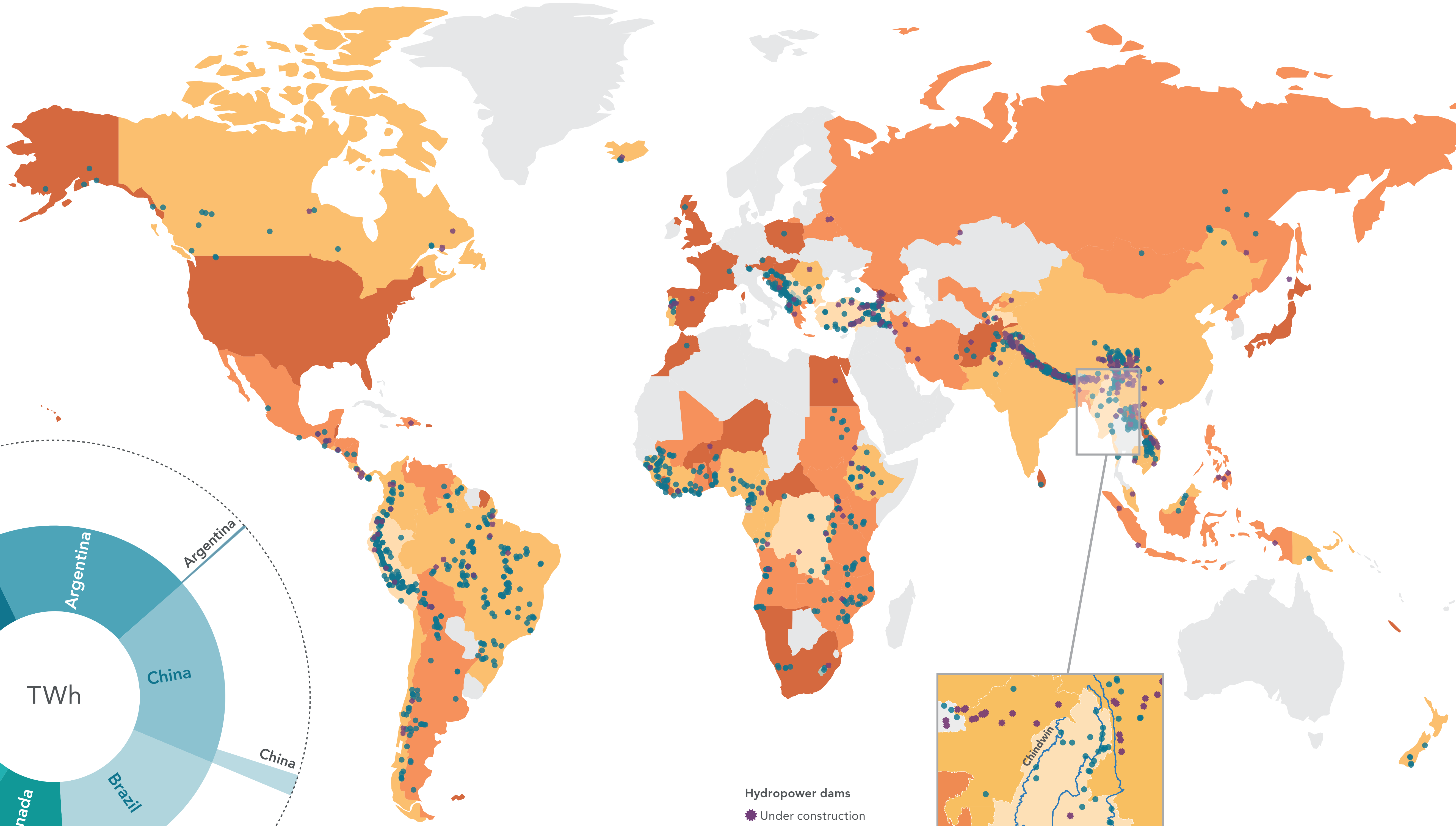
5.2. The amount of under-construction and planned hydropower within each quintile of fishery production (with one being the lowest and five the highest harvest). Nearly half of all future hydropower is projected to occur within the basins that are in the highest quintile of production. Three-quarters of future development is within the top two quintiles combined.[9]

5.3. Potential generation by country: hydropower and low-impact wind and solar

Potential generation, in TWh, from low-impact wind and solar (inner ring, from Baruch-Mordo et al. 2018) and potential future hydropower (outer ring, from Zarfl et al. 2015)[10].*

*See p61 for endnote 10





5.4. Global map of potential hydropower and potential generation from low-impact wind and solar

Ratio of the potential generation from low-impact wind and solar to potential future hydropower by country. Under construction and potential dams are also displayed. The inset map illustrates potential dams on rivers in Myanmar - the last long free-flowing rivers in South or Southeast Asia. See Annex 2 for methods and sources.

Chapter 6

MAKING SUSTAINABLE GRIDS A REALITY

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Chapter 6


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The challenge of shifting power generation across the globe to renewable energy sources while meeting growing demand for power and addressing environmental needs is unprecedented.

This transformation will be driven by technological advances and economies of scale that have driven down costs to competitive levels, combined with policies that removed barriers and opened markets to new renewables. However, ensuring this occurs rapidly enough to secure the climate depends on key policy, institutional, technical, and financial reforms. These reforms will be the shared responsibility of many stakeholders, including governments, developers, utilities, consumers, investors, and civil society.

To accelerate the power sector transition and address the important challenges associated with a dramatic expansion of renewable energy, energy sector stakeholders will have to adapt simultaneously to several major changes, including:

- The rapid changes in the relative costs of different energy technologies and their impact on investment choices;
- The unique short-term variability of solar and wind energy and its impact on electricity market operations;
- The breadth and depth of climate change mitigation strategies; and
- A more-informed, engaged, and empowered public and the influence of public opinion on acceptance of a massive scale-up of renewable energy projects.

These unprecedented changes necessitate reforms in three key areas: policies and regulations to support the renewable revolution; power systems planning, investment, and financing; and the integration of renewable resources into power systems.

6.1 POLICY AND REGULATIONS TO SUPPORT THE RENEWABLE REVOLUTION

The key drivers making the renewable energy revolution possible — namely the sharp decline in solar and wind energy costs, and the commitment of countries to climate mitigation targets — have occurred so rapidly that many decision makers have not yet been able to adjust their energy policies and plans or prepare for the impacts on their power markets. Electricity markets, whose rules are established by governments, were designed primarily to provide cost-effective reliable power in a stable market environment. The same rules that favor stable and low-cost supplies gave preference to large central power stations that depended on fossil fuels or hydropower, whose costs have been historically low. Opportunities for innovations and pioneer technologies have often been limited by traditional power market structures.

Enabling policies are crucial to catalyze shifts in technologies and practices across power systems. These policies start with ambitious targets, expressed through international and national commitments, supported by specific plans, economic instruments (such as quotas and certificates, targeted procurement rules, feed-in tariffs, carbon pricing, and financial incentives for renewables), barrier removal policies (such as ending subsidies on competing energy sources such as oil and coal, equal grid access for renewables, and net metering policies), and restrictions on highly polluting technologies. Some measures will be specific to utility-scale installations, distributed generation, and off-grid or mini-grid solutions, while others will affect all of these segments.

Energy targets are critical for establishing the goals for implementing policies and regulations in any country or state. Recent increases in targets for renewables reflect the urgency that governments

KEY POINTS

- **Accelerating the renewables transition requires the removal of barriers, including policy and regulatory reforms, redirecting financial flows towards new renewables, and technological innovation. There are successful examples for all of these that can be emulated by other countries.**
- **Many governments need to modernize their energy-sector policies to take full advantage of the renewable revolution, for example by committing to binding renewable energy targets and/or introducing targeted auctions for renewables to identify least-cost options.**
- **Financing of new renewables not only needs to be scaled up dramatically, it also needs to include funding for system planning.**
- **Power system planners, regulators and operators need to learn how to integrate increasingly large shares of variable renewables into their grids.**

place on driving this transition. Over 175 countries have some version of a national target for renewable energy, which can range from broad policy goals to binding objectives, such as renewable portfolio standards. Although the United States does not currently have a national target, at least 37 US states have some version of a renewable energy goal[1]. The State of California, for example, adopted a law in 2018 requiring that half of California's electricity is powered by renewable resources by 2025 and 60% by 2030, while calling for a "bold path" toward 100% zero-carbon electricity by 2045[2].

Procurement policies, whether tied to targets or not, are just as important for driving the energy transition. Market arrangements must consider the characteristics of the generation technology. For example, long-term power purchasing agreements (PPAs) have become effective tools for contracting solar power, as evidenced by their use in Chile, Mexico, and the United States. They are effective because they balance the needs of the generator (i.e., reliable payments over the long term, at a price that covers their costs including debt service) with those of the off-taker (i.e., reliable access to electricity at a predictable price). A variety of contracting tools should be used in a diverse market to reflect the different characteristics of the power sources, including dispatchable, variable, stand-by, peaking, storage, etc. These tools need to provide confidence to stakeholders, including generating companies, their equity investors and banks, and off-takers.

With rapid cost declines, the renewable revolution does not depend on economic subsidies any more. Early movers such as Germany, beginning in the early 2000s, provided generous feed-in tariffs to support solar, wind, and other renewable energy deployment as a tool to overcome the pricing barrier for these alternatives. Feed in tariffs (FiT) were designed to provide long-term security to renewable energy producers based on the costs of generation of each technology, rather than the least-cost conventional options at the time[3]. As a result, they helped to create the economies of scale, which now make solar and wind affordable[4], and like many countries, Germany has moved on to competitive models that no longer require significant subsidies (see Box 6.1 on subsidies for small hydropower).

Regarding competitive models, countries are now experimenting with different auction designs that will lead to next generation procurement[5].

For example, some auctions may be limited to certain technologies, regions or even individual sites that governments want to promote. Such eligibility restrictions can be an effective way to channel investment into the desired low-impact locations, thus increasing public acceptance. Auction regulations could exclude hydropower on certain "no-go" rivers that would result from the planning process (see the case study on Chile in Chapter 4). Auctions can be employed to procure generated energy, firm capacity, or different ancillary services, in different time slots and with different temporal horizons.

In regions that have not achieved universal access, enabling policies may still have to include subsidies to extend the grid or create off-grid solutions. In some areas, even the lowest-cost sustainable technologies may still not be affordable. In others, sustainable projects may not be competitive with non-sustainable projects, because of more expensive sites or the costs of mitigation measures. These sustainable universal access subsidies will then have to be covered by taxpayers or, where cross-subsidization is possible, by ratepayers. For example, India recently achieved near universal electrification, but many households who were not willing or able to pay fees have yet to be connected.

Policy reforms need political and public support. Civil society organizations can help support the transition by challenging the power sector to show more ambition, through constructive involvement on siting of new energy infrastructure, and by helping to achieve public acceptance and political support for the transition. Many countries still have a long way to go, in particular countries with a heavy reliance on coal such as China, India, the United States, Australia and Indonesia.

Regardless, all countries need to take steps to accelerate the renewable revolution and the role of governments will be essential in setting policies and regulations to reduce costs, increase competitiveness, and advance the deployment and integration of renewables into national energy systems[i].

i A comprehensive review of various policies and their critical role in this market transformation can be found in the report, Renewables 2017 Global Status Report and Advancing the Global Renewable Energy Transition http://www.ren21.net/wp-content/uploads/2017/06/170607_GSR_2017_Full_Report.pdf . (REN21, 2017a, 2017b).

A 9.9 MW hydropower project in Albania that de-waters a stretch of the Rapuni River downstream.

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BOX 6.1

SMALL HYDROPOWER

In 2008, Switzerland introduced a feed-in tariff to promote the expansion of renewable energy sources[6]. While the law incentivized sources such as wind and solar, the developers of small hydropower projects were the biggest beneficiaries: following passage of the feed-in tariff, 116 small hydropower dams have been constructed across streams all over Switzerland.

Although these small dams don't cause impacts such as displacement, they still fragment streams, leaving stretches with reduced flow during much of the year.

The power gains from adding more than 100 dams were minimal; the new projects generate 498 gigawatt hours (GWh) per year, less than 1% of the country's annual generation. In comparison, a project to rebuild an existing large hydropower dam on the Rhine with a new design added more than 400 GWh[7], nearly equivalent to the generation produced by the 116 new dams.

And it's not just Switzerland - a recent study found that there are at least 83,000 small hydropower dams around the world (more than 10 times the number of large hydropower dams), with tens of thousands more in the planning pipeline[8] (note that the definition of "small" varies considerably around the world, from < 10 MW to up to 50 MW in some countries).

But the Swiss example does effectively illustrate two important issues when it comes to small hydropower. First, small hydropower is generally assumed to be a low – or even no – impact source of low-carbon electricity. But, small dams can sometimes have major impacts, such as on migratory fish (see examples from the Penobscot and Elwha rivers in Box 4.3), and several studies of cumulative impacts have found that small hydropower can have larger impact per unit of energy produced than large hydropower. Because of the presumption that it is low impact, small hydropower is often fast-tracked (e.g., exempt from requirements for Environmental Impact Assessments).

Second, due in part to the presumption of low impact, small hydropower is often incentivized in policies to promote renewables under climate change objectives. In fact, these incentives can trigger investment that leads to a proliferation of small dams that collectively make an insignificant contribution to the national grid, even as they may cause substantial cumulative environmental impacts.

This is not to say that small hydropower is never an appropriate solution. In fact, small hydropower (or even micro-hydropower) can provide electricity to remote communities or contribute to decentralized mini-grids serving areas outside primary grids. And companies are finding innovative ways to deploy small hydropower that are truly low or no impact, such as adding turbines to irrigation dams or canals[9].

However, the issues describe above underscore that decision makers and energy planners should evaluate small hydropower on its actual impacts and realistic contributions to energy and development gains, not on overly simplistic (and often inaccurate) assumptions. In most cases, subsidies or incentives for small hydropower dams would be better directed at other policy goals.

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6.2 POWER SYSTEMS PLANNING, INVESTMENT, AND FINANCING

Institutional, public and private investors need to redirect investments from fossil fuels industries and other unsustainable projects to projects that contribute to future sustainable energy systems. The IPCC recently estimated that additional investments into energy systems to meet the 1.5° C goal are around US$830 billion annually from 2016-2050 — including six times more than current investment levels in low carbon technologies and energy efficiency[10]. These costs also represent an immense investment opportunity and will reduce investor exposure to material and reputational risks from unsustainable projects, such as coal plants, that are likely to suffer cost and schedule overruns, and may become obsolete over their lifetime[ii]. With interest rates that are still low by historical standards, and many potential investments with high rates of return, there should be no shortage of capital as long as the regulatory frameworks are conducive. However, both private capital and public investments are not being used to help increase the deployment of renewables to the extent that they could. Both should be looking to how they can maximize the flow of funds to support the planning and development of renewables.

In developing countries, private capital markets, public agencies, and partners from bilateral and multilateral agencies and banks, which are committed to the Paris Agreement and the SDGs, need to support the transition with targeted funding and knowledge transfer. Some multilateral agencies, like the World Bank, have already refocused their lending in the energy sector to support renewables. In 2018, the Bank signaled that it would no longer

ii For example it costs more to run 35% of coal power plants than to build new renewable generation; by 2030 building new renewables will be cheaper than continuing to operate 96% of today's existing and planned coal plants, as indicated in the report, Powering Down Coal

support investments in oil and gas, and it is committed to ensuring that 28 percent of all its transactions by 2020 support climate actions. Furthermore, the Bank and other multilaterals such as the Inter-American Development Bank (IDB), Asian Development Bank (ADB), African Development Bank (AfDB), and the European Bank for Reconstruction and Development (EBRD), have access to a broad range of dedicated loan and grant instruments that can be deployed to support the renewable energy transition, including the Green Climate Fund (GCF), the Global Environment Facility (GEF) and the Clean Technology Fund (CTF). These and other funds, including those specific to bilateral development agencies, are described in the OECD Clean Fund Inventory Database[11]. In all cases, these institutions should also consider the appropriate use of blended finance to leverage these public sources many times over by bringing private and institutional investors into the fold.

Institutional investors who can take a long-term view — such as sovereign wealth funds — have an important role to play in enabling the renewable energy revolution[12]. Currently there is US$8 trillion in these funds around the world, but less than 0.2% is invested in renewable energy[13]. These currently underutilized funds could have a profound role to play in boosting the transition to renewable energy economies.

The successful deployment of new financing strategies and streams is contingent on the development of appropriate long-term planning processes, and countries will need to invest substantially in early stage or "upstream" planning. They need to map their resources to find the lowest-impact, highest-potential sites; apply modern multi-criteria planning methods to the selection of technologies and projects; and ensure that the overall system will be able to operate efficiently and reliably, while minimizing environmental and social impacts (see Section 4.1). These tasks cannot be left to developers, and even monopolistic national utilities can only perform them if given clear mandates and resources.

In the absence of comprehensive planning, impacts and conflicts are more likely. There are already increasing numbers of of rejections of wind and solar farms by affected communities and permitting authorities[14]. In Iceland, for example, the environmental license for the first large-scale wind farm was rejected. While the wind resource at the site was tremendous, it was rejected largely due to concerns about landscapes and visual impacts. Such concerns are almost certain to increase in the future. According to IRENA (2019), solar and wind capacity would have to increase more than 14-fold (from 900 to 13,000 GW) by 2050 to meet the Paris Agreement objectives, by which time they would provide 60% of total power generation. However, in many countries, local acceptance — or the "social license to operate" — is becoming an ever more important and ever more elusive prerequisite, and regulatory licenses often reflect the public's attitude.

Ensuring public (and regulatory) acceptance is likely to require a dual strategy. First, proponents have to make a genuine effort to follow the mitigation hierarchy, by identifying and avoiding high-value sites, by minimizing and mitigating impacts, and by offsetting any residual impacts. While this could be achieved by a technical, expert-driven process, this is unlikely to be sufficient. Second, proponents also have to engage the public and the regulators in the process, explaining the logic behind siting, design and operational proposals, and listening to feedback.

Considering that renewable energies need only limited amounts of land, compared to other processes such as urbanization and agricultural expansion, the siting problem is likely to be solvable almost everywhere. To address the concerns of communities and protect the environment, decision makers would benefit from access to data and decision-support tools to inform them of what natural resources they have available that would generate low-impact opportunities for renewable energy development. A comprehensive planning approach, such as The Nature Conservancy's Development by Design (DbD) can support integrated planning for energy and conservation at landscape, watershed, and seascape levels.

Such tools and information would give developers a sense of the probability of success, including likely conflicts or acceptance of any new projects. Where renewables projects are welcome, they are more likely to get support in the form of grid connections, feed-in rights, and construction permits. In supportive frameworks, countries can provide designated solar, wind or other renewable power development areas, with simplified permitting processes, offtake arrangements, and transmission infrastructure already in place.

BOX 6.2

EARLY PLANNING PROJECT PREPARATION FACILITIES IN SUPPORT OF "UPSTREAM" PLANNING

An early planning project preparation facility could support "upstream" planning that first identifies an inventory of potential project sites, consistent with both investment risk/return criteria and criteria focused on social and environmental sustainability.

These sites would then be prepared in detail – including feasibility and impact assessment studies – to arrive at a short list of bankable projects available to developers. Such a facility would motivate participation from a diversity of constituencies: governments, by helping meet renewable energy commitments and other strategic targets and streamlining the selection and permitting process; developers, by providing a risk-reduced pipeline of projects; development banks, by creating a loan pipeline for the same risk-reduced pipeline; and social and environmental civil society organizations, by establishing a development framework in which their perspectives could be incorporated during the influential early stages of planning.

Funding needs to be made available more proactively and broadly by multilateral and bilateral financial institutions to support "upstream" planning by governments. A recent analysis of existing funds or mechanisms (such as traditional project preparation facilities) with funding potential for upstream planning for Latin America concluded that there are only a handful of mechanisms that are currently set up to provide some of the necessary services. These include ESMAP & PPIAF (at IBRD) and NDC Invest & UK Sustainable Infrastructure Program (at IDB), as well as others that have the potential to do so by broadening their mandate: INFRAFund (at IDB), Clean Technology Fund (at the Climate Investment Funds), the Private Sector Facility (at the GCF), Global Infrastructure Facility, CABEI and CAF. Annex 1 provides a table with examples of funds with the potential to support upstream planning.

6.3 INTEGRATION OF RENEWABLE RESOURCES IN POWER SYSTEMS

Decision makers need to become convinced that an energy system that integrates large amounts of renewables will deliver better results. Perhaps the most substantial concern regarding integration of solar and wind energy is their effect on the reliability of the power supply. Initially, when the proportional generation from wind and solar is relatively low, the variability of these sources is very manageable using modern power system management tools. In this stage, the main strategy that system regulators and operators use is to inform solar and wind developers where and how they can connect through so called "grid codes." There may be a need to manage grid congestion in certain regions and at certain times of the day, and it becomes necessary to better forecast solar and wind generation to avoid curtailment.

As the penetration of variable sources increases, first the flexibility and then the stability of the grid become important priorities. This requires improved forecasting accuracy, more flexible operations of existing assets, dealing with reverse flows from distributed generation (when their output becomes large relative to the distribution system capacity into which they are feeding), increasing the size of jointly operated grids (or balancing areas), and introducing requirements or markets for ancillary services.

To summarize, there are four solutions to short-term variability, which are now well understood[15]:

- ***Demand management.*** Utilities can reduce demand at peak times through a combination of technologies and monetary incentives. For example, customers with smart electric meters can cool down their freezers or recharge the batteries in their electric cars in early morning off-peak hours, for a reduced cost.
- ***Complementary generation capacity.*** Generation companies can keep power stations in reserve for operations in peak hours. These are typically hydropower (with reservoir), natural gas or diesel plants. In contrast, other power technologies such as nuclear, coal, geothermal, biomass, and run-of-river hydropower are designed for continuous operations, and are less useful for load-following.
- ***Grid integration.*** Power grids can consist of multiple complementary generation facilities and be interconnected over large areas, which increases the probability that the sun or the wind are available at least somewhere in the area, and peak demand hours are spread over a longer period of time.

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- ***Storage.*** Excess power during off-peak hours can be stored, traditionally in pumped hydropower storage but also, increasingly, through other technologies (such as molten salt in concentrated solar plants, batteries, or through conversion to hydrogen and other fuels). Batteries in particular are currently experiencing advancements in performance and dropping in price, suggesting they may offer great promise in the near future.

All of these options have some financial, environmental, and social costs, and typically a combination will be used to increase the resilience of the system while minimizing those costs.

There are a number of countries that are already managing a high share of variable renewables, showing that this is feasible and that a number of arguments that were traditionally raised against variable renewables are no longer valid[16]. Several examples of common concerns regarding variable renewables are listed below, including a corresponding response:

- "*Weather driven variability is unmanageable*": All grids are able to deal with variability, which is always present on the demand side. Grids will typically possess multiple variable power plants, which will typically vary in distinct periods. Furthermore, grids may include several baseload and/or storage options that can serve to backstop variability.
- "*Deployment of variable renewables imposes high cost on conventional power plants due to the need to ramp up and down on short notice*": These challenges can be managed through forecasting of variable generation that informs real-time updates of generation schedules.
- "*Variable renewable capacity requires 1:1 backup*": While the capacity factor of a single solar or wind plant may be low, the capacity factor of a system of multiple plants is significantly higher. It can be further increased where solar generation is complementary with demand (for example, where air conditioners operate during hot times of the day), where demand can be shifted to off-peak times, or where energy can be stored.
- "*Storage is a must-have*": Storage is just one element of flexibility. Demand management, complementary generation capacity, and grid integration over larger areas have the same eff.ect

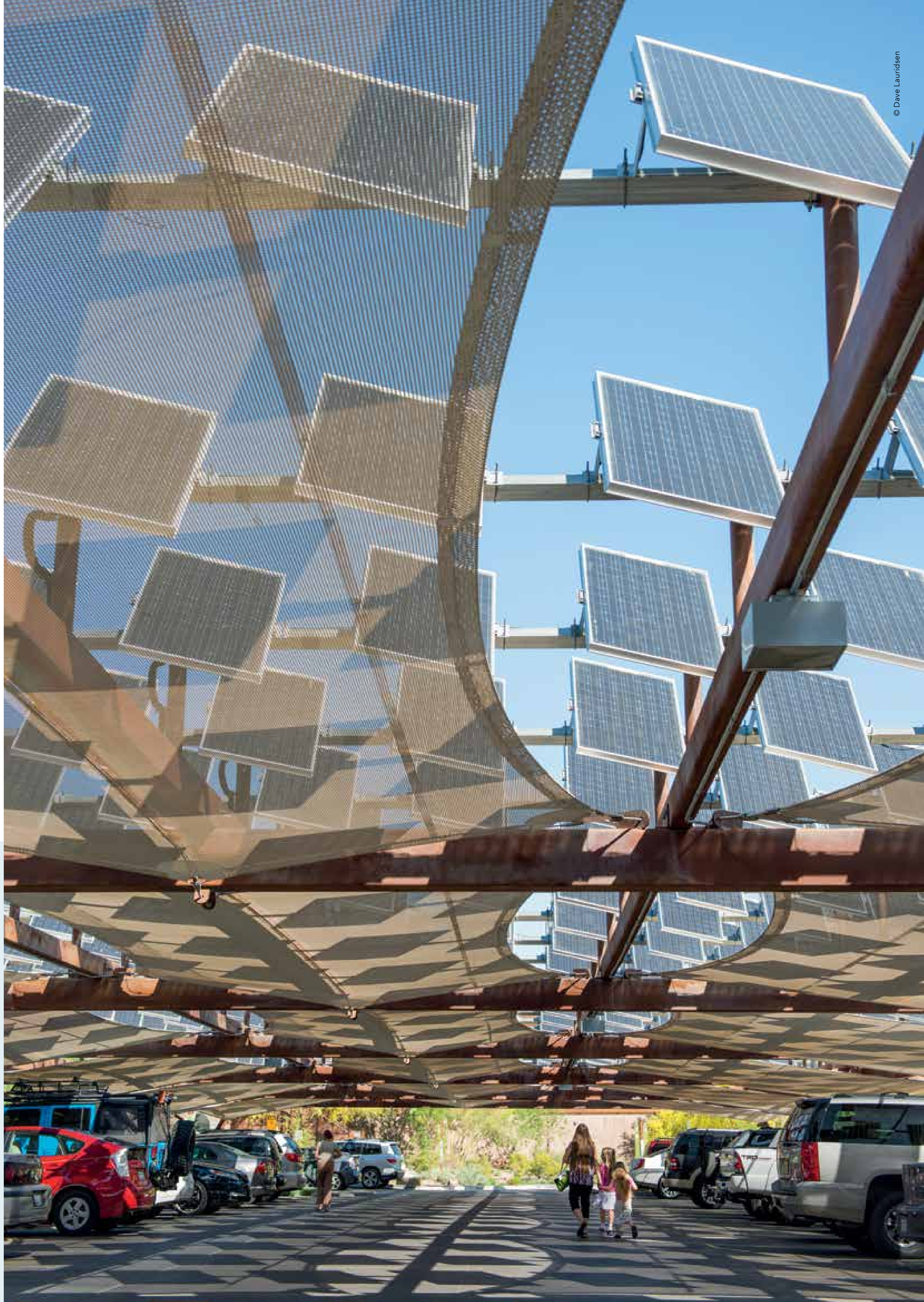
Grid reliability is also an important element of power system planning. While we have previously discussed the environmental best practices for siting of renewable projects, the siting of renewable projects also has important implications for grid reliability, and this should be considered simultaneously during evaluation of impacts and costs. Strategic siting options for solar and wind need to factor in whether their siting should be dispersed or concentrated, the proximity of siting to load centers, and the appropriate grid voltage (distributed or centralised)[17].

6.5 CONCLUSION

A clean energy future that meets multiple social and economic development objectives while minimizing local and global environmental impacts is possible. Modern renewable technologies — including variable sources such as solar and wind, combined with back-up generation and storage from batteries and low-impact hydropower — and advanced systems management approaches make such a reality possible. They also reduce the risks associated with status quo development pathways, both for our climate in the case of fossil fuels, and for communities, rivers, and terrestrial ecosystems in the case of high-impact hydropower. The transition to a sustainable electricity system depends not only on continued technology advancements, but also on many policy, regulatory, planning, financing, and management reforms.

1. Governments should establish policies and enforce economic and regulatory instruments in pursuit of targets.
2. Governments, utilities, and planners should establish and adopt system-scale planning for the power sector to maximize system performance and minimize impacts.
3. Governments need to expand the availability of bilateral and multilateral financing aimed at achieving the Paris Agreement and the Sustainable Development Goals.
4. Governments should increase access to financing to achieve universal access to low-carbon, low-impact, low-cost electricity.
5. Governments and the finance sector should increase financing for all phases of project development leading to a substantial upscaling of investments in renewable energy generation capacity as well as in storage, transmission and distribution capacity, energy efficiency, electrification of transport and heating, smart meters, and other components of the future system.
6. Planners need to expand access to data and decision-support tools to inform stakeholders of what natural resources exist and how they may be used to generate low-impact renewable energy development.
7. Planners and developers should focus investments on low-impact sites by upgrading existing facilities, using brownfields or other degraded lands, and using lands close to transmission infrastructure.
8. Planners and operators should support improvement and innovation in grid management approaches to prevent grid congestion and to avoid curtailment.
9. Civil society organizations and communities should actively support efforts to accelerate the energy transition.

The success of the energy transition will depend on the collective efforts of many stakeholders towards these reforms.



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Chapter 7

FISH AND GRIDS: SUSTAINABLE POWER FOR THE MEKONG REGION

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7.1 INTRODUCTION

This report has offered a vision of how the world could meet its electricity needs through power systems that are low carbon, low cost and low impact on environmental and social resources.

To ground this vision in reality, this chapter explores how this vision could be implemented in the Mekong River basin in Southeast Asia. Here we integrate all the various components of the report — modeling of grids and river basin processes, trends in investment and delivery of various generation sources, and recommendations for improved governance, policies, and implementation mechanisms — to illustrate how those components can collectively accelerate delivery of sustainable power systems in a region.

And that region is one of the places in the world where achieving more-sustainable energy development is most critically and urgently needed. The Mekong River is the world's most productive freshwater fishery and its delta is vital for Vietnam's agriculture and economy, as well as for regional food security. Both the fisheries and the delta, in addition to many riverside communities, are at risk of suffering major negative impacts if hydropower development continues along its current trajectory, particularly with a few extremely high impact dams, such as Sambor, in the planning process (see Box 7.1). Here we show that those losses are not the regrettable-but-necessary trade-offs required for regional economic growth. Rather, countries in the Mekong region can have both low-carbon power systems that fuel growth and reduce poverty *and* a Mekong River that retains its incredible productivity and diversity. Many opportunities for more-sustainable energy development have already been missed due to the lack of a system-scale approach to hydropower siting. Going forward, the region does not need to continue down this path of missed opportunities and significant negative impacts that could have been avoided. However, decisions made in the next few years will lock in one energy trajectory or the other. The time is now to ensure that the region follows a sustainable path from this point forward.

7.2 THE MEKONG AND ITS RESOURCES

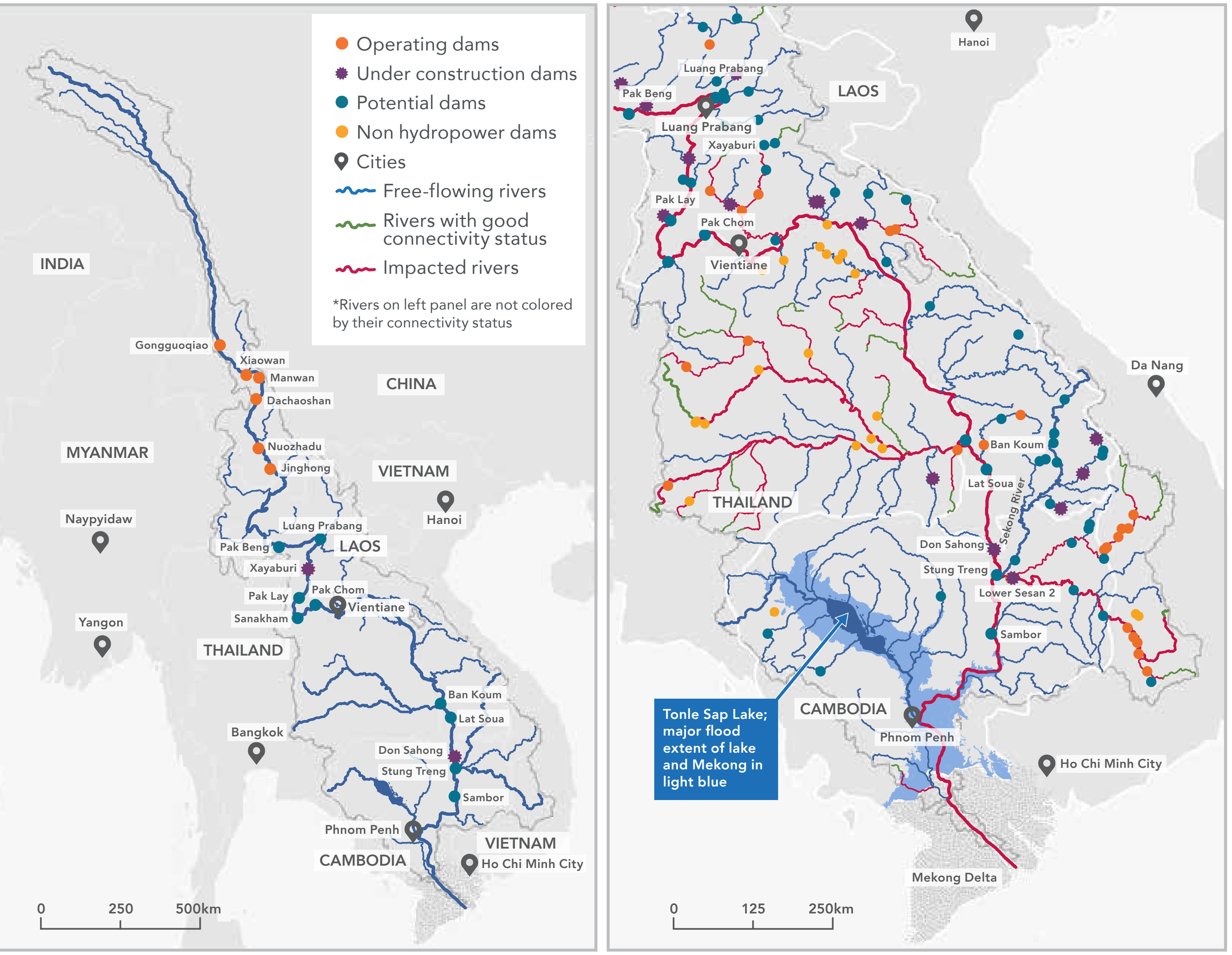
The Mekong River supports the largest wild freshwater fishery in the world and a delta with highly productive agriculture and aquaculture. These globally significant food resources are critical to regional stability and are maintained by the Mekong's water, the sediment and nutrients it carries, and the floodplains it flows across.

The Mekong is 4,800 kilometres long — making it the 12th longest river in the world — and winds through six countries with a population of 70 million. The river starts as glacial meltwater from the Tibetan plateau and runs through China, Myanmar, Laos, Thailand, and Cambodia before entering the ocean at its delta in Vietnam (Figure 7.1). The river's discharge, ranked 10th in the world, is driven by the highly seasonal monsoon rains and has one of the greatest variations between high and low flows among large rivers. Historically, the Mekong carried the tenth largest natural sediment load in the world, depositing 160 megatons (Mt)/yr downstream and maintaining a delta that is an economic powerhouse. The delta supports 21 million people and provides nearly a quarter of Vietnam's GDP. Its cropland produces more than half Vietnam's staple crops and the majority of its rice exports — a significant amount given that the country is among the world's leading rice exporters[1].

KEY POINTS

- **The Mekong River supports the world's most productive freshwater fishery and delivers sediments that maintain the delta, a crucial part of Vietnam's economy and regional food security.**
- **Continuation of the current hydropower trajectory would lead to the loss of nearly half of the Mekong's migratory fish biomass and drastically reduce sediment flows so that half of the delta could be underwater by the end of this century.**
- **Recent studies indicate that the region can meet its future electricity demands with low carbon power systems that do not require high-impact hydropower dams on the mainstem or the remaining free-flowing tributaries.**
- **System planning can identify hydropower options that will have minimal additional impacts on fisheries and sediment.**
- **Although there are signs that the renewable revolution is taking hold in the Mekong region, decisions in the next few years on highly impactful dams such as Sambor could preclude more balanced outcomes. Coordinated and proactive policies and planning are needed to ensure that countries can pursue a more sustainable energy path.**

7.1. The Mekong River basin



Mekong River

Lower Mekong Basin

7.1. Map of the Mekong basin (left) and Lower Mekong Basin (right). Mainstem hydropower dams (existing, under construction and potential) are shown on the left map while the right map shows mainstem and tributary dams. Note that the Don Sahong dam, on the Mekong in southern Laos, spans one channel in a multi-channel section of the river. The right map color codes channels based on their value for Connectivity Status Index (sensu Grill et al. 2019). For example, the Sekong tributary, near the Cambodia-Laos border, is colored blue as it remains a free-flowing river.

The Mekong basin is home to 850 species of fish, second only to the Amazon — a basin that is nearly seven times larger. Among that diversity are some of the largest freshwater fish on the planet. The herbivorous Mekong giant catfish can grow up to 300 kilograms — larger than most brown bears. The giant freshwater stingray can weigh twice as much as the giant catfish and could cover a four-door car. Beyond fish, the river supports an impressive richness of reptiles, amphibians, birds, and mammals, including the largest and most viable of the three remaining populations of freshwater Irrawaddy dolphins[2].

In addition to giant fish, the Mekong's diverse fish fauna supports a massive harvest. The lower basin yields more than 2 million tons of wild capture fish annually, representing nearly 20% of the global freshwater fish harvest. The annual Mekong harvest is valued at over US$11 billion and provides the primary source of protein and livelihoods (or both) for tens of millions of people[3].

The productivity of both the delta and the lower basin fisheries are driven by the river's flow regime and hydrological connectivity. The delta was created by thousands of years of the river depositing nutrient-rich sediment as it flowed into the sea, and the delivery of nutrients and sediments to the lower river drives aquatic food webs, which underpin both the productive inland and coastal fisheries.

No location illustrates this better than Tonle Sap Lake in Cambodia (Figure 7.1). For half the year, the lake drains through the Tonle Sap River downstream to the Mekong. But, in the monsoon season, the Mekong rises high enough that it forces the Tonle Sap River to reverse course, flowing in the direction formerly known as "upstream" and filling the lake with Mekong water. The Tonle Sap Lake's surface area swells to three- to five-times its dry season size and it quadruples in depth — from two meters to eight.

As the lake expands, the raw materials for fish production flow in: water, nutrients, adult female fish ready to spawn, and larval or juvenile fish that were spawned upstream and have been riding the rising tide downstream. The expanding lake inundates the surrounding forest, and fish gain access to its organic material: leaves, fruits, and insects. Months after the rains stop, the lake begins to drain back toward the Mekong carrying an incredible bounty of fish. The lake also acts as a major flood buffer protecting the Mekong Delta.

The Mekong is an incredible organic factory of food production with the delta and Tonle Sap Lake serving as two of the central engines that keep the factory running. These ecosystems also illustrate how three characteristics of a functioning river fuel this food production and diversity:

- ***Flow:*** The flow of the Mekong includes not only water, but also sediment and nutrients.
- ***Lateral connectivity between the river and the landscape:*** This connectivity allows the flow of the Mekong to deposit nutrients and sediment in lakes, across floodplains, and on the delta. Where lateral connectivity exists, fish can leave the river to use highly productive floodplain habitats and then return to the river.
- ***Longitudinal connectivity:*** Much of the sediment that builds the delta is derived from mountains thousands of kilometers upstream and must be carried by the river. Similarly, a high number of the Mekong's fish species — including many of the most important for the fish harvest — require long distance migrations, moving between spawning habitat, often far upstream, and productive habitats where juvenile fish rear and grow, often low in the basin, such as Tonle Sap Lake.

These characteristics can all be dramatically affected by dams, so the diversity and productivity of the Mekong River now face an uncertain future due to the dramatic, ongoing expansion of hydropower dams.

7.3 HYDROPOWER RISKS TO MEKONG BASIN RESOURCES

The economies in the Mekong region are growing rapidly, between 6-8% per year, and the IEA expects a doubling of electricity demand in the ASEAN region until 2040[4]. Hydropower has long been central to the region's power supply: Thailand began building hydropower in the 1970s and 1980s, followed by Vietnam in the 1990s, Laos since 2000, and most recently Cambodia. Collectively, the four countries of the Lower Mekong Basin (LMB), have frequently looked to hydropower as the lowest cost way to expand capacity and achieve energy security. Today, dozens of dams have been built on tributaries of the Mekong with dozens more in some stage of planning. China began building dams on the upper Mekong, known locally as the Lancang, in the 1990s and has now built six dams on the mainstem.

While some tributary dams generated controversy, conflict around hydropower increased considerably with the first proposed dam on the mainstem in the LMB, the 1,285 MW Xayaboury Dam in northern Laos. In 2010, Laos notified the Mekong River Commission (MRC) of its intention to build a mainstem dam, as required under the agreement establishing the MRC. The MRC was created in 1995 by the four countries of the LMB to "jointly manage the shared water resources and the sustainable development of the Mekong River," including hydropower resources. Myanmar and China did not join, but maintain observer status[5].

Laos' notification of its intention to build the first dam on the lower Mekong sparked controversy, particularly from downstream countries. In response, the MRC funded a Strategic Environmental Assessment (SEA) for Mekong mainstem hydropower, assessing not just Xayaboury but ten other proposed mainstem dams in the lower Mekong (Figure 7.1). The SEA found that while completion of the 11 dams would reduce basin-scale biomass of migratory fish by nearly half (42%) and have serious implications for biodiversity in the basin, the amount of electricity generated would meet only 6-8% of the region's projected energy demand in 2025[6].

Through a MRC-led consultation and dialogue process, various changes have been made to the design of Xayaboury, focused on improving the passage of both fish and sediment[7]. However, even as the dam nears completion, questions remain about the effectiveness of these solutions as both are largely untested in a major tropical river such as the Mekong.

Meanwhile, dam construction has continued apace: in 2013, Laos notified the MRC of its intention to build the Don Sahong Dam on the Mekong just above the border with Cambodia (Figure 7.1) and construction began in 2015. In 2017, Laos began to move forward on two other mainstem dams: Pak Beng and Pak Lay. Cambodia is considering options for dams at Sambor and Stung Treng, which would be the closest dams to the Tonle Sap and the delta and would be among the most damaging hydropower dams ever constructed (see Box 7.1).

Construction of tributary dams has continued, and the impacts have prompted scientists to highlight another risk: the trapping of sand and other sediment in dam reservoirs. Studies showed that as of 2015, dam construction was already depriving the delta of at least half of the historical supply of sediment and that construction of all the planned dams would lead to a greater than 90% depletion. Together with other pressures such as sand mining, scientists forecast that this reduction would significantly contribute to the projected loss of more than half of the delta to sea level rise by the end of the century. River bank and coastal erosion, river bed incision, land subsidence, and other problems have already begun to emerge in the delta at an alarming rate[8].

It is clear that the Mekong basin has significant untapped hydropower potential: building all proposed dams would supply another 260,000 GWh/yr to the region. However, hydropower development has carried a steep price in terms of people displaced and losses of fish and sediment. Continued energy development along the current path would likely result in unacceptably high impacts on riverside communities, the delta, migratory fish, as well as the food supply and livelihoods they support.

The renewable revolution — both the global trends and its initial green shoots in the Mekong region — suggests that a different future is possible. In the next section, we review results of planning and modeling studies that identify a path toward power systems that are low carbon and low cost with relatively low additional impacts on the Mekong and its resources. While the Mekong has so far been notable primarily for missed opportunities for strategic planning to reveal better options (Box 7.2), the chapter concludes with a discussion of how policies, financial mechanisms, and investment priorities could lead to strategic planning and development that achieves the sustainable path.

BOX 7.1

SAMBOR DAM AND PROMISING SOLAR ALTERNATIVES

In October 2016, the Cambodian government authorized a Memorandum of Understanding with the locally based Royal Group to undertake studies on the 2,600 MW Sambor hydropower project (Figure 7.1). Based on a feasibility study by the former developer China Southern Power Grid Company, this would be one of the largest dam projects in the region, including an 18 km long dam and an 82 km long reservoir.

The Sambor reach of the Mekong River is the migratory corridor that experiences the largest annual movement of biomass on the planet, and the Sambor project is expected to substantially reduce fish stocks and fish capture. Given its proximity to the Tonle Sap and the delta – and its position between them and upstream spawning grounds – the Sambor reach has been called the "least suitable place for a physical barrier in the Mekong Basin" and is expected to have the "largest impact on the Mekong fishery of any of the mainstream dams." It would effectively convert 82 km of river into a lake through which fish larvae could not drift, trap most of the sediment uncaptured by upstream dams, and significantly change downstream geomorphology and flow dynamics[9].

Fishermen, traders, and others for whom fishing is the primary source of livelihood would be most directly affected, but fisheries account for nearly 12% of Cambodia's GDP and contribute more to the country's economy than rice production[10]. Upstream, the dam's reservoir would inundate what is probably the most biodiverse stretch of the Mekong or any other large Asian river, including unique landscapes such as the Mekong Flooded Forest and Stung Treng wetlands[11]. This would affect the habitat of the Irrawaddy dolphin and other endangered species, probably leading to their extirpation.

Within the last few years, rapid price drops have made solar power a viable alternative to Sambor. Cambodia's first utility-scale solar PV plant (Bavet, 10 MW) is already operational and has reached grid parity with new hydropower projects. Solar and existing reservoir hydropower plants complement each other very well given Cambodia's monsoon climate. New solar farms can be built in less than one year, substantially accelerating energy access and economic development.

The Natural Heritage Institute has provided a detailed proposal for a floating solar PV project on the reservoir of Lower Sesan 2 as part of the alternative power that could substitute for Sambor[12]. For this current report, we assessed the potential of floating solar on all Mekong reservoirs, following the method used in a recent World Bank publication[13] and found the potential for nearly 30,000 GWh/year from floating solar on Mekong basin reservoirs (see Annex 2 for methods and a table of PV potential on Mekong reservoirs). While a preliminary estimate, for perspective, that value is double the generation from all current dams in the 3S tributary basin, comprising the Sesan, Srepak, and Sekong rivers, and five times as much as is anticipated from Sambor.

BOX 7.2

MISSED OPPORTUNITIES FOR STRATEGIC PLANNING IN THE MEKONG BASIN

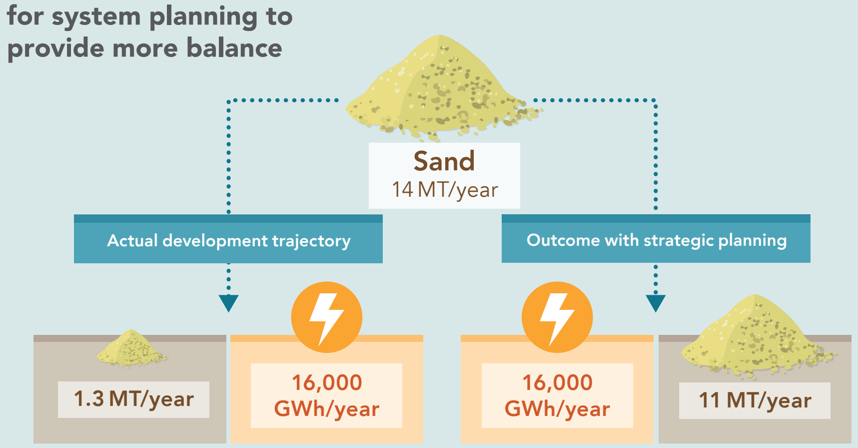
Several studies have recently identified development pathways that could achieve a better balance between hydropower and other resources in the basin. However, until now, these studies have primarily underscored how far the current reality is from those more-balanced options (Figure 7.2).

For example, Ziv et al. (2012) modeled different potential combinations of 26 proposed dams on the Mekong's tributaries[14]. For each combination, the authors quantified generation and, using a fish population and migration model, estimated the impact on biomass and the viability of migratory fish species. Building all 26 dams would reduce the biomass of migratory fish in the whole Mekong basin by nearly 20%. However, by foregoing a few dams, fish losses could be minimized to just 3%, while still producing 75% of the total available energy from tributary dams. This analysis identified one dam — the 400 MW Lower Sesan 2 — as contributing to half the total impact on fisheries, with its individual impact an order of magnitude greater than the second most impactful dam. Lower Sesan 2 began construction the same year Ziv's paper was published and was completed in 2018.

Lower Sesan was also highlighted as particularly impactful with regard to the sediment budget of the lower Mekong. Schmitt et al. (2018) found that the current portfolio of dams in the 3S tributary basin, including Lower Sesan 2, produces 16,000 GWh/year and reduces sand output by 91%. By examining all other potential combinations of dams, they found that a different combination of dams could have produced the same generation but only reduced sediment flow by 15%[15]. Schmitt et al. (in press) conducted a similar exercise for the entire Mekong and found that the suite of existing dams generates 125,000 GWh/year, but has reduced delivery of sediment to the delta from 160 to 50 Mt/year. If it had been adopted before beginning construction, a strategic planning approaching to dam siting could have identified a group of dams that would have produced the same annual generation while maintaining twice as much sediment delivery to the delta (100 Mt/year)[16].

These examples highlight missed opportunities. While those specific optimal development options are no longer available, there is still significant scope to utilize a system approach so that future energy development produces far more balanced outcomes.

7.2. Missed opportunities for system planning to provide more balance



7.2. For the 3S Basin, a strategic planning approach could have produced the same generation as the actual development trajectory, but maintained eight times as much sand exported from the basin to the downstream delta.

7.4. FEASIBILITY OF LOW-COST, LOW-CARBON AND LOW-IMPACT POWER SYSTEMS FOR THE MEKONG REGION

Here we summarize the results of two modeling studies, which demonstrate that the region can meet its projected future electricity demand with power systems that are low carbon, low cost and low impact on the Mekong. They show that the region's future power systems do not need to include those dams that will have significant additional impacts on people, fisheries, sediment, and ecosystems.

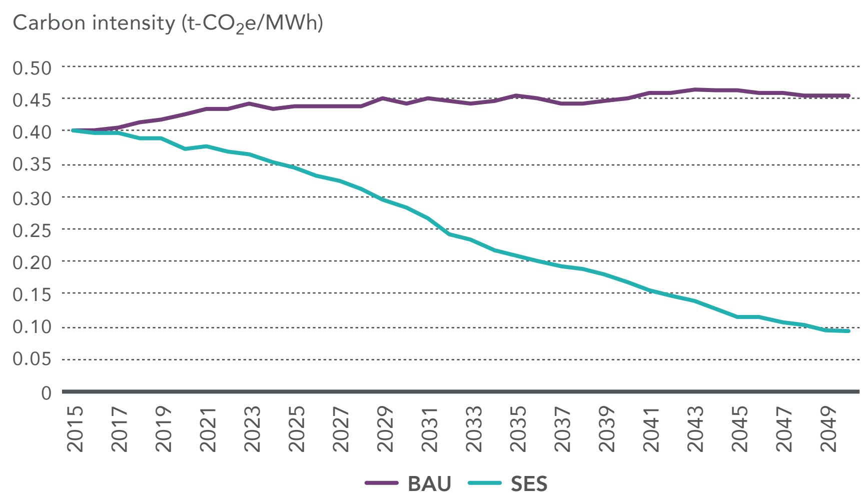
The Mekong Power Sector Vision, published by WWF in 2016[17], compared a Business as Usual (BAU) scenario with a Sustainable Energy Scenario (SES) for meeting the projected 2050 electricity demands of five countries in the Greater Mekong region — Cambodia, Laos, Myanmar, Thailand, and Vietnam. Compared to BAU, the Sustainable Energy Scenario would be:

- ***Lower carbon.*** In 2050, fossil fuels would provide 65% of the generation under the BAU scenario, consisting largely of imported fuels. Conversely, the SES would reduce emissions by 85% with 80% of generation coming from renewable sources (Figure 7.3).
- ***Lower cost.*** The Levelized Cost of Electricity (LCOE) from the SES would be lower than BAU for most of the time period (Figure 7.4). The SES has initially higher capital costs, but lower operating costs due to the dramatically lower reliance on imported fuels. By 2050, the region could be saving approximately US$40 billion per year if it adopted the SES compared to BAU.
- ***Lower impact.*** The BAU scenario anticipates development of enough hydropower dams to provide an additional 140,000 GWh/year between 2020 and 2050, while the SES calls for a 75% reduction in added hydropower generation compared to BAU, anticipating an additional 35,000 GWh/year during that period (Figure 7.5). This reduction would allow far fewer dams to be built, making it far easier to avoid damaging dams, such as Sambor or other mainstream dams downstream of Xayaburi, and those that would block remaining free-flowing tributaries, such as the Sekong.

A second study, focused just on Laos, suggests that low-carbon, low-cost power systems are possible for that country with even lower impacts on the Mekong[18]. A team from the University of California's Renewable and Appropriate Energy Laboratory (RAEL) compared the business-as-usual capacity expansion for Laos, which consists primarily of large hydropower and coal, to a least-cost development option that would meet projected demand and export targets through 2030. Even using conservative regional projections for costs of various renewable generation sources, the least-cost scenario started bringing wind and solar PV online as soon as 2022 (Figure 7.6). In addition to having a far lower impact on the Mekong by eliminating the need for most hydropower development, the least-cost scenario was estimated to require US$2 billion less in investment than the BAU — and would not require ongoing imports of purchased coal.

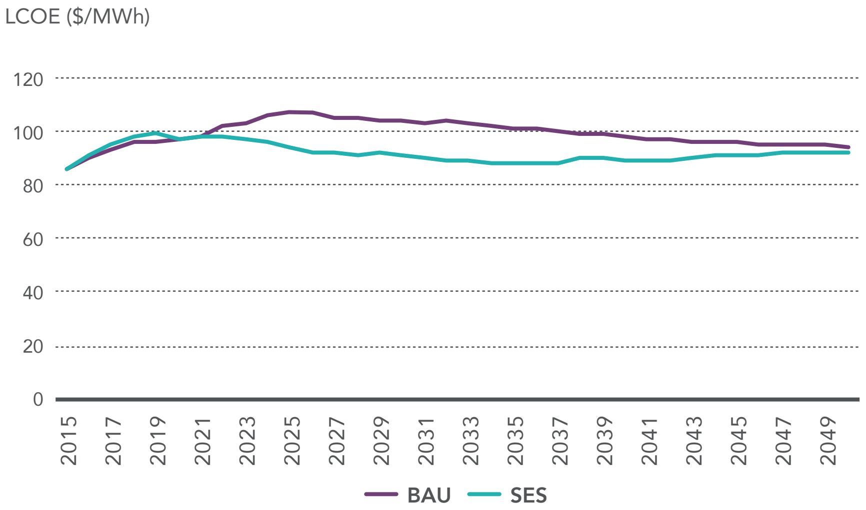
Both studies call for considerable expansion in wind and solar in the Mekong region, which raises potential

7.3. Carbon intensities for scenarios of power expansion in the Mekong basin



7.3.Comparing the carbon intensity of the business-as-usual (BAU) and sustainable energy scenario (SES; from WWF 2016).

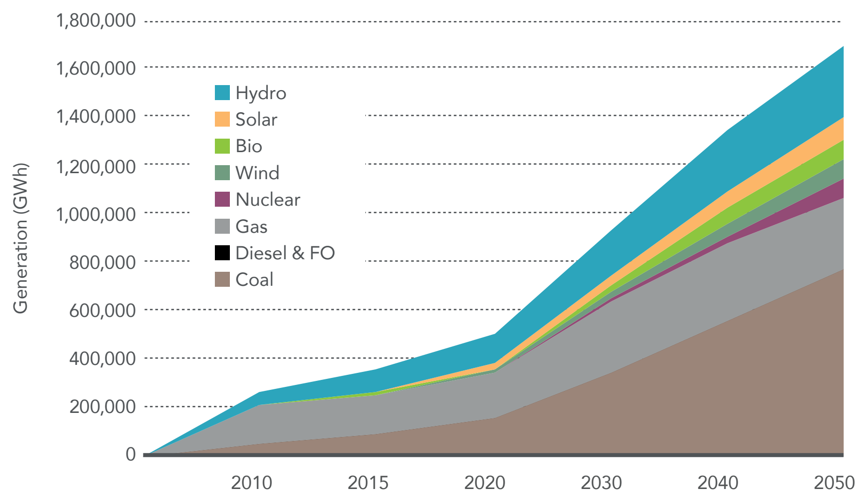
7.4. Comparing LCOE for scenarios of power expansion in the Mekong basin



7.4. Comparing the levelized cost of electricity (LCOE) of the business-as-usual (BAU) and sustainable energy scenario (SES; from WWF 2016).

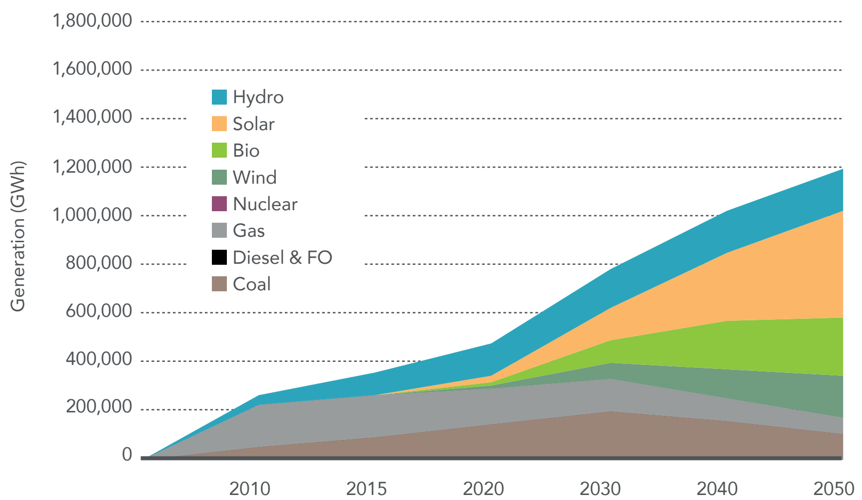
7.5. Generation mixes of two scenarios of power expansion for the Mekong basin

Business as usual (BAU)



7.5. Generation over time and mix of generation sources between the business-as-usual (BAU; top) and sustainable energy scenario (SES; below). Note that energy efficiency is a high priority for the SES and thus overall demand for the SES is about 30% lower than for the BAU. This will require relatively small improvements in efficiency each year until the region attains levels of efficiency found in other developed Asian countries (from WWF 2016).

Sustainable Energy Sector (SES)



concerns about competition with other land uses such as agriculture or forests. However, using results from Baruch-Mordo et al. (2018)[19], who assessed the global technical potential of wind and solar on already converted lands (see Chapter 2), we found that the Mekong region has abundant resources of wind and solar that could be developed with low impacts on land and people.

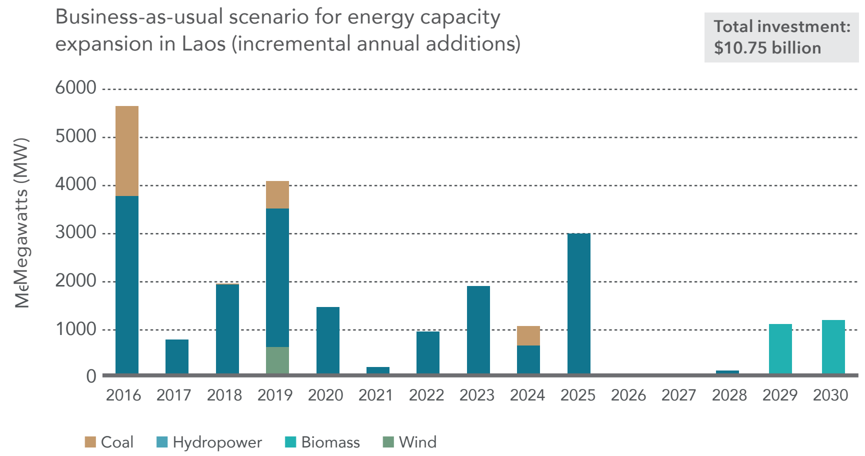
Collectively, the lower Mekong basin countries of Cambodia, Laos, Vietnam, and Thailand have 1,630 TWh of low-impact renewable energy potential (Figure 7.7; this includes 30,000 GWh from floating solar; see Box 7.1). This is approximately nine times the projected additional future hydropower generation in the BAU in the WWF study and nearly three times the amount of wind and solar anticipated in the SES. Although substituting wind and solar for hydropower within a grid requires consideration of grid services beyond just generation, these results indicate that there is a large pool of low-impact wind and solar, which could be developed to contribute to low-carbon, low-cost, and low-impact grids.

7.5 REDUCING IMPACTS OF ANY FURTHER HYDROPOWER EXPANSION

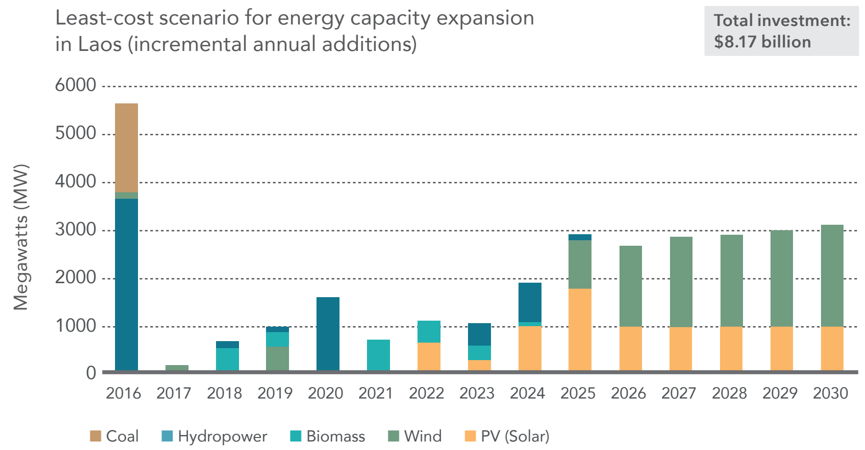
Although these studies suggest a reduced need for hydropower over various time intervals, the WWF (2016) projection does anticipate some new hydropower, underscoring that methods to identify the lowest impact options may remain necessary. System planning approaches could be applied to identify the options (individual dams or groups of dams) that can work well across multiple objectives.

Here we describe an example of tradeoff analysis to identify which dams from the current portfolio in the Mekong could meet a target for hydropower generation with the lowest impact on sediment. To do so, we sequentially integrate energy models with river basin models, first identifying what increment of hydropower generation is needed to support a low-cost and low-carbon scenarios and then using river basin models to identify a set of lower-impact dams that could meet that target. Ideally, this integration would happen simultaneously rather than sequentially

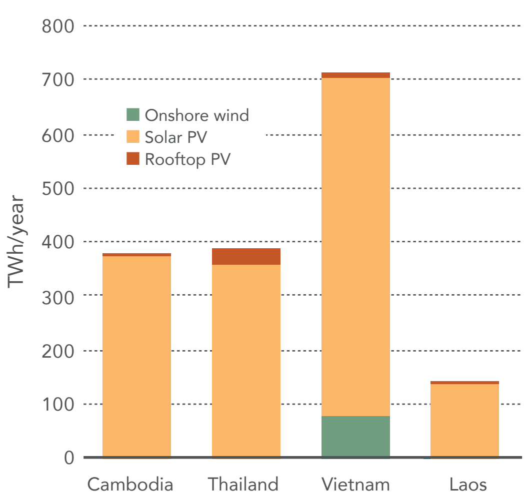
7.6. Capacity additions for two power expansion scenarios for Laos



7.6. Comparing capacity additions in Laos for a business-as-usual scenario (BAU; top) and least-cost scenario (bottom).



7.7. Mekong – low-impact wind and solar



7.7. Low-impact, utility-scale wind and solar energy potential available on converted lands in countries in the Lower Mekong Basin. Modeled technologies include utility-scale wind and PV and rooftop PV.

(with interacting models that can incorporate data on tradeoffs and performance of projects or sets of projects within the process to select projects for capacity expansion). However, the sequential approach used here illustrates the fundamental objectives of integrating planning tools to ensure that environmental performance of projects on a landscape are considered within the project selection process.

Schmitt et al. (in press) used a genetic algorithm coupled to a network sediment transport model to explore tradeoffs between hydropower generation and sediment delivery to the delta[20]. This approach can identify the portfolio of dams that minimize the loss of sediment for any level of energy generation, including the optimal sequence of dams to reach any given level of development. The current dam portfolio already traps around two thirds of the entire Mekong basin's historic sediment load, while generating 125,000 GWh/yr — mostly from dams in the Lancang and in lower Mekong tributaries. As described in Box 7.2, this current portfolio of dams is quite far from the optimal sequence, trapping almost twice as much sediment as the optimal portfolio would have for the same generation. Although that result offers a lesson in missed opportunities, this approach can still be applied to inform which projects can meet a target for an additional increment of hydropower generation with the lowest impact on sediment.

Construction of the current sequence of proposed dams, including Sambor, would further reduce sediment from today's 50 million tons/year down to approximately 13 million tons, while adding an additional 75,000 GWh/year of electricity production. However, a process that sought to optimize generation and sediment could produce the same amount of generation with almost no additional loss of sediment (see "optimized whole basin" compared to "planned future" in Figure 7.8). This outcome is possible by siting most new hydropower upstream of existing dams, thus minimizing losses of sediment to the river system. However, this approach would require most of the additional hydropower to be built in China, which does not correspond to current national plans (e.g., China is slowing its hydropower development, while lower basin countries, particularly Laos and Cambodia are focused on increasing hydropower generation).

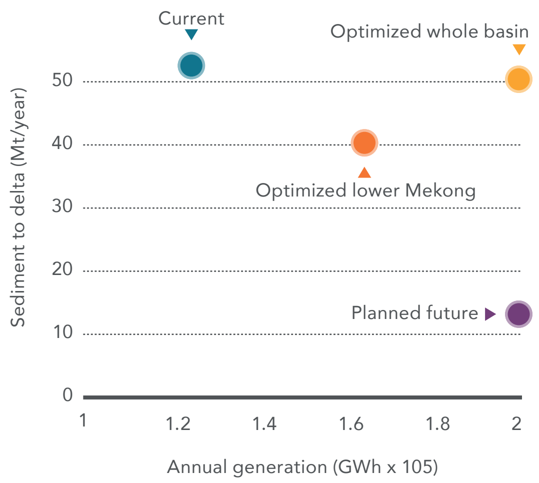
To correspond more closely to the realities of current national objectives, the study also examined a scenario that limited additional hydropower expansion to the lower Mekong. The ability to expand generation in the lower basin without large impacts on sediment was limited. However, the "optimized lower Mekong" scenario increased generation by approximately 30,000 GWh/year with an additional loss of sediment of 10 million tons/year, with the system declining to 40 million tons/year — still four times greater than planned future projections. Although the increase in generation of the optimized lower Mekong scenario is lower than that of the planned future, it is comparable to the increase in LMB hydropower generation anticipated in the Sustainable Energy Scenario in WWF (2016).

Thus, methods such as this could be used to meet hydropower targets with fewer impacts on sediment. Although this analysis only focused on two objectives (generation and sediment), it should be noted that both the "optimized whole basin" and "optimized lower Mekong" models accomplish the primary objectives for maintaining migratory fish habitat: avoiding Sambor and maintaining the Sekong tributary as free-flowing and connected to the lower basin. Because the costs of wind and solar have continued to drop steeply, it may be that a revised SES would allow for an even less-impactful dam portfolio.

7.6 IMPLEMENTING A SUSTAINABLE ELECTRICITY EXPANSION FOR THE MEKONG REGION

Although hydropower has been a primary source of power for the Mekong region and current projections show a continued expansion of hydropower, dramatically falling costs of other renewables over the last few years are beginning to impact the energy market. Although a transition toward greater investment in wind and solar is starting in the Mekong, a market-driven shift towards other renewables will not automatically equate to a decline in impacts on the river from energy development. The pace and scope of adoption of the renewable revolution will vary from country to country, and even if Thailand and Vietnam make a rapid transition, Laos and Cambodia may still pursue high-impact projects, which could have system-scale negative impacts on the Mekong's resources. Thus, coordinated regional and national planning processes, financial mechanisms, shifts in investment priorities, and energy diplomacy all have a role to play in ensuring a rapid transition to a more sustainable energy development path. In this section we explore mechanisms that can accelerate the region's transition toward power systems that are low cost and low carbon with low future impacts on the Mekong River.

7.8. Various scenarios for expanding hydropower in the Mekong basin



7.8. Various scenarios for hydropower expansion in the Mekong and how they perform in terms of generation and sediment supply.

To illustrate recent trends, in 2015 Thailand established a target of 6,000 MW of solar capacity by 2036. The country achieved half of that target in three years and is now increasing its solar target. Since establishing a feed-in tariff in 2017, Vietnam has added 3 GW of solar and has signed 14 GW of MoUs with project investors. In mid-2019, Vietnam plans to shift to a reverse auction system, which could herald a further boom in private investment. Laos and Cambodia are also showing interest in diversifying their power sectors with solar and wind.

The potential for these trends to disrupt status quo energy trajectories was brought into sharp relief by Thailand's decision in March 2018 to suspend negotiation of the power purchase agreement (PPA) for the proposed Pak Beng Dam on the Mekong mainstream in Laos. Coupled with Thailand's commitment to boosting investment in domestic electricity generation rather than increased imports and the fact that it has been the major off-taker for Laos hydropower, this decision to suspend the PPA potentially heralds major changes in the region's energy trajectory.

These trends are promising, but without coordinated and proactive efforts the transition to a more sustainable future is not likely to occur fast enough or consistently enough across national boundaries to ensure that the Mekong remains healthy.

7.6.1 The current project-by-project approach to Mekong hydropower

Most dams in Laos and Cambodia are built under Build-Own-Operate-Transfer (BOOT) agreements. BOOT agreements usually include a foreign developer, which funds and constructs the project, earns profit on the sale of hydropower from the project over a period of decades, and then turns the asset over to the host government at the end of the contractual period. Although Mekong countries could restrict licensing BOOT projects to those consistent with a strategic plan, in practice, developers have had significant influence in determining which projects move ahead, particularly in countries that depend on foreign direct investment for economic growth. The lack of checks and balances in these countries and relative dependency on foreign investment has led to the development of dams on a project-by-project basis without an overall vision that weighs tradeoffs of hydropower generation versus other benefits provided by river resources or compared to other generation options.

The project-by-project approach to hydropower development in the Mekong creates a situation where the basin-wide impacts of Laos and Cambodia's future hydropower development are unable to be quantified or properly avoided and/or mitigated. Foreign developers are generally not transparent in the sharing of otherwise proprietary data around an individual project, making cumulative impact assessments or other assessments that consider the interacting impacts of multiple projects virtually impossible. In Laos, which has an inventory of more than 150 potential dams in the basin, foreign investors have considerable negotiating power and often prefer projects with transmission lines that link assets directly to an off-taker market rather than pooling power in the local utility. In Laos, this has slowed the buildout of an effective power system and actually impeded the development of effective national grids, which constrains the ability of power planners to incorporate other forms of renewable power.

The imbalance in negotiating power that favors foreign investors also has real-world implications for the management of impacts. Contracts for BOOT projects in Laos and Cambodia often reward the foreign developer with the majority of income, while the host country government and its neighbors have primary responsibility for managing the project's impacts. These impacts are often felt long before the host country gains any significant benefit, which is often not for decades or even until project ownership reverts to the host countries.

This unbalanced distribution of income prevents national-level line agencies from building human resource capacity and investing in information systems related to meteorology and climate change, which would help investors make sounder decisions about the long-term commercial viability of hydropower projects and reduce risk. Because of the Mekong's transboundary nature — where impacts of a single dam or a concentration of upstream dams might materialize hundreds of kilometers downstream and in ways that fall outside of the traditional purview of cost-benefit analysis — planning must transition towards a more coordinated approach that is designed and shared by various stakeholders in the region.

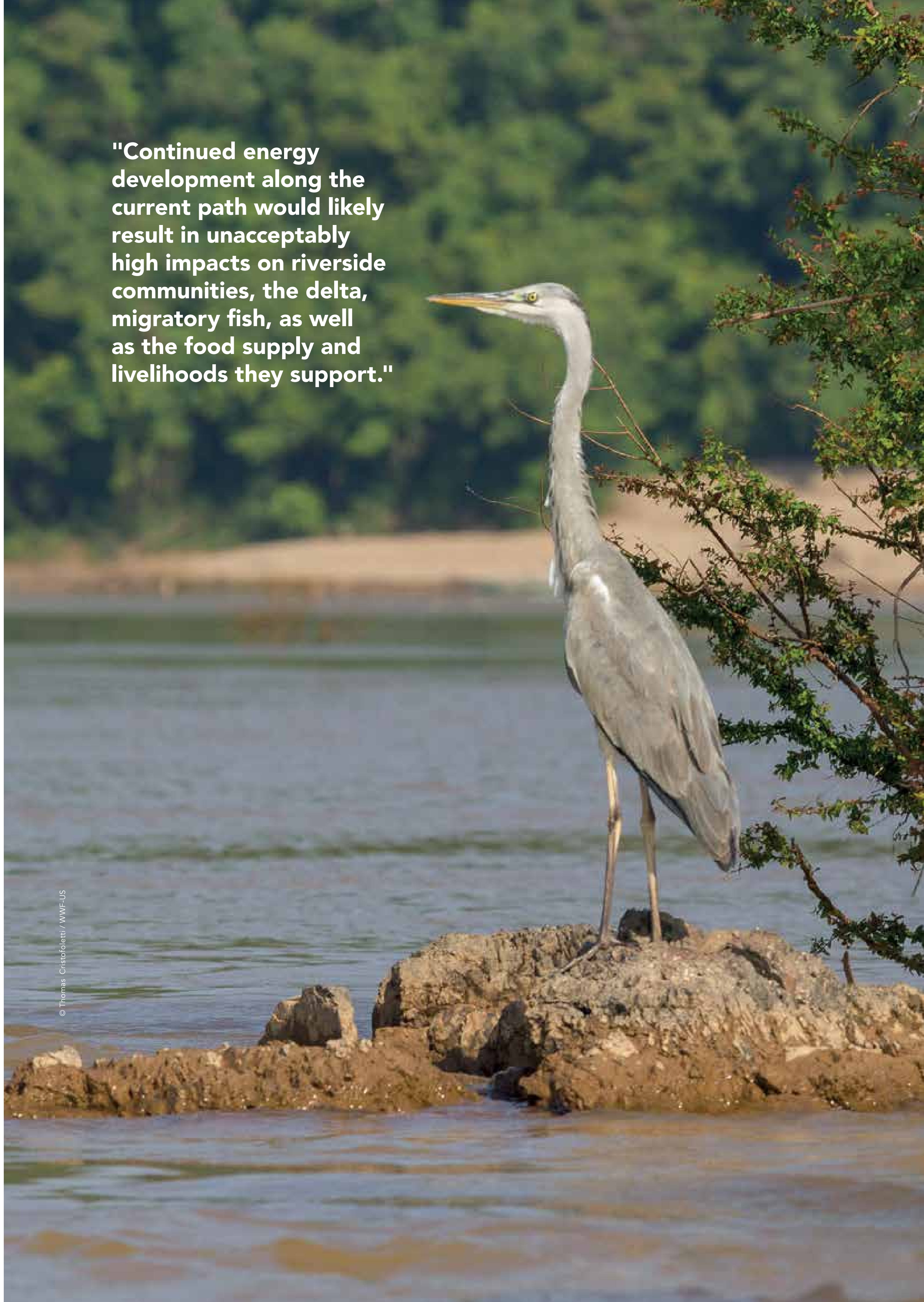
While the MRC has the basin-scale focus, information and tools to guide regional planning and influence site selection, the MRC agreement does not give it that purpose or authority. A single country's adoption of a system-scale approach could provide a precedent and inform regional studies and negotiations. However, to date, no Mekong country has an effective, cross-cutting institutional platform, which could promote coordinated and programmatic planning scenarios and tradeoff analyses for national energy development and — by extension — contribute to coordination of the energy mix and hydropower's role within it at the regional level.

7.6.2 A slow shift to renewable energy

Compared to other parts of the developing world, Mekong countries have been slow to incorporate non-hydropower renewables into their power mixes despite an abundance of renewable endowments (see Figure 7.7). Pushback from well-vested agencies in Vietnam and a bad experience with feed-in-tariffs in Thailand prevented both countries from taking early advantage of falling global prices, which made utility-scale solar and wind economically viable. Thailand and Vietnam are now incorporating higher renewable energy targets into their power mixes and reducing regulatory barriers, which have historically protected and subsidized hydropower and coal. Thailand's recent turn to domestic production of renewable energy could wholly shift its interest away from imports, as its revised power development plan reduces annual imports from Laos through 2037 from 9,000 MW to just 3,500 MW.

Although impacts from projects in Laos and Cambodia are of concern to many Thai and Vietnamese stakeholders, neither government has fully made the connection to how a system-scale approach to energy planning could achieve a low-impact power mix. Given their roles as investors and power purchasers, if either Thailand or Vietnam were to promote a system-scale approach to energy planning it could prove catalytic to the whole region.

Laos and Cambodia are demonstrating increased interest in non-hydropower renewable energy, but both have been slow to adopt official targets and build the policy pathways to incentivize investment in renewable energy. Officials in Laos and Cambodia often cite nearly verbatim the arguments against renewables reviewed in Section 6.3. In fact, in early 2017, officials in Cambodia's energy planning department noted that integration of large-scale solar PV into Cambodia's power mix was a decade away. However, less than a year later, Cambodia broke ground on its first utility-scale solar project (10 MW) and took steps to clarify guidelines for solar



"Continued energy development along the current path would likely result in unacceptably high impacts on riverside communities, the delta, migratory fish, as well as the food supply and livelihoods they support."

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BOX 7.3

THE BELT AND ROAD INITIATIVE AS A POTENTIAL DRIVER OF THE RENEWABLE REVOLUTION

In 2013, China launched the Belt and Road Initiative (BRI), an outbound investment strategy expected to exceed US$1 trillion in total investment volume over the next decade[21]. China's stated goals of the BRI are to promote development and cooperation through infrastructure investments in countries along the route of the historic Silk Road, which connected East Asia and Southeast Asia with East Africa, West Asia and Southern Europe.

China's leaders have pledged that the Belt and Road Initiative will be green. At the opening of the Belt and Road Forum in 2017, President Xi Jinping called for the BRI to "pursue a new vision of green development and a way of life and work that is green, low-carbon, circular and sustainable." He reiterated these themes at the 2nd Belt and Road Forum in 2019, calling for the pursuit of "open, green and clean cooperation" that "promotes[s] green development".[22] In 2018, Xie Zhenhua, China's Special Representative for Climate Change Affairs, emphasized that all BRI projects should "adopt the latest technologies, save resources and energy as much as possible, and ensure the best performance in emissions reduction."[23] Chinese leaders have framed the BRI as a means of achieving the Sustainable Development Goals (SDGs) and emphasized China's commitment to the success of the Paris Agreement.[24] China is hosting COP15 of the Convention on Biological Diversity in October 2020, and leaders have promoted a "global push" against the erosion of biodiversity.[25]

However, evidence suggests that existing patterns of Chinese outbound investment fail to meet these stated objectives. The overwhelming majority of China's overseas energy investments, for example, have gone to fossil fuels projects, including oil, coal, and natural gas projects.[26] China's investments in large hydropower projects in the Mekong basin in Laos and Cambodia threaten fisheries and livelihoods. The imperative — and opportunity — to improve the environmental and social performance of Chinese outbound investment is enormous.

The following recommendations provide a roadmap that would allow Chinese leaders to meet their pledges for a greener Belt and Road. The focus elsewhere in this report has been on improved host country strategic and system-level planning and coordination, which prioritizes renewables development and reduces reliance on hydropower projects with high impacts. Nonetheless, a robust solution will benefit from engagement not only with host country stakeholders, but also with relevant Chinese agencies and financial institutions, Chinese state-owned enterprises (SOEs) and private companies, and a broad range of local and global stakeholders who can help facilitate the transition to more sustainable development.

- Opportunities exist for engagement with the Asian Infrastructure Investment Bank (AIIB) and Chinese financial institutions involved in the BRI, including the China Development Bank, the Export-Import Bank of China, and the Industrial and Commercial Bank of China. Further work is required to strengthen environmental review procedures and transparency requirements, while establishing policies that promote "green" investments and limit unsustainable projects.
- The multitude of Chinese agencies with a role in overseas investment and environmental regulation must be granted clearer authorities to assess the environmental impacts of Chinese overseas investment and, where necessary, steer investment away from environmentally harmful projects. Rules that implicitly encourage the outsourcing of unsustainable industries should be eliminated. The relevant agencies include China's Ministry of Ecology and Environment (MEE), the National Development and Reform Commission (NDRC), the People's Bank of China, the Ministry of Finance, the Ministry of Foreign Affairs, China Banking Regulatory Commission, China Securities Regulatory Commission, the Ministry of Commerce, the State-owned Assets Supervision and Administration Commission (SASAC) — which oversees SOEs — and others.
- Chinese lawmakers should require Chinese SOEs and private companies to disclose the environmental impacts of their outbound investment activities. Greater transparency enables improved monitoring of company behavior and generates insights into environmental impacts among the companies themselves.
- China should collaborate with national governments to ensure that environmental planning and review procedures provide for broad public participation involving local communities, civil society actors, and other stakeholders. China has developed such mechanisms domestically and has begun to establish participatory institutions for the BRI. The urgent task going forward will be to ensure that these mechanisms are effective in practice. President Xi promised to adopt "widely accepted rules and standards… in project development." China's support for robust participatory and transparency mechanisms would send a strong signal of commitment to these pledges.
- China should seize the opportunity and use the BRI to drive progress on climate change by facilitating sharing of policy best practices, incentivizing research and development on green innovations support system-scale planning for renewable power systems, and prioritizing financing projects that are low carbon. Some private companies in China are global first movers on renewable energy technology innovation and should be put at the forefront to lead the efforts of greening BRI.

Chinese engagement and investment through the BRI promise to transform the economies of developing countries, but serious institutional reforms will help to ensure that this development is as environmentally sustainable as possible.

A wind farm in Pakistan developed by China Three Gorges South Asia Investment Limited (CSAIL), an investment holding company of the China Three Gorges Corporation (CTG). As of 2017, CTG had developed 8,000 MW of wind and solar power.

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investment. Another 60 MW project has recently started construction. Prices agreed to in solar PPAs are now approaching parity with new hydropower PPAs in Cambodia. Rolling blackouts during the dry season in 2019 have been attributed to underproduction from Cambodia's hydropower fleet, bolstering the case for further development of solar.

Laos and Cambodia's power sectors are significantly under-resourced, partially as a result of the project-by-project approach to power development discussed above. Existing constraints contribute to a lack of human and technical capacity, preventing these countries from pursuing a regular cycle of power planning, which could reap efficiencies on the supply and demand sides. Limitations of their grid infrastructure — including fragmented transmission and limited investment in modern smart-grid management equipment — constrain their ability to manage the integration of high levels of variable renewable energy.

7.6.3 Investment, MDBs, and development partner engagement

In all four Lower Mekong countries, technical assistance and targeted investment from development partners could accelerate the renewable transition. The Asian Development Bank (ADB) has been instrumental in promoting solar in Cambodia, for instance. However, initiatives from outside actors generally lack alignment. Multilateral development banks, such as the World Bank and ADB, often provide technical assistance to establish feed-in tariffs and auctions for renewable assets and also support a pipeline of individual projects. While pilot investments are needed, MDBs could facilitate broader change by focusing resources on increasing transmission and distribution capacity, and investing in the capacity and conditions needed to increase private investment in power generation.

Some key development partners have provided technical assistance to build both management capacity and power infrastructure, but assistance from the United States and China could be more focused on the renewable transition. Funding under China's Belt and Road Initiative (BRI) has to date primarily supported large-scale hydropower and coal projects in Mekong countries, but the BRI could potentially be a driver of more strategic investment, which prioritizes power systems that are low carbon, low cost and low impact (see Box 7.3). China generally avoids funding capacity-building programs abroad as they are viewed as a form of "interference," which China eschews. United States agencies such as USAID and its National Renewable Energy Laboratory have provided technical assistance on the renewable energy transition from a national power planning perspective but have yet to fully engage on the transboundary aspects of power trade and power planning.

7.6.4 Recommendations

The challenges and gaps identified above can be remedied and doing so would accelerate the adoption of sustainable and strategically coordinated power systems throughout the Mekong. This analysis suggests that:

- Governments should prioritize the assessment and development of low cost, low impact alternatives to planned high impact hydropower dams on the Mekong mainstream as well as the remaining free-flowing tributaries, such as the Sekong. These dams would negatively impact people and river resources, including fisheries and sediment – particularly those with severe, system-scale impacts such as Sambor.
- Governments in the Mekong region can improve their capacity to consider tradeoffs by creating national platforms responsible for sharing information and providing them with sufficient bureaucratic power to mediate between various ministries on the multi-sector impacts of hydropower and broader energy options. If sufficiently empowered, these platforms could lead on national sustainable development strategies as well as coordinate with the Mekong River Commission and other regional partners to design low-carbon, low-impact development plans consistent with the opportunities emphasized in this chapter.
- Laos and Cambodia should consider clarifying the contracts for BOOT hydropower projects to require data-sharing with the national government and (where relevant) the Mekong River Commission so that these projects feed into future system-scale planning efforts. Furthermore, countries should strive to allocate future concessions in a more transparent and inclusive process and ensure they are informed by strategic analyses of cumulative impacts and options.
- MDBs and development partners can improve effectiveness through better coordination with each other and by supporting capacity building, transmission infrastructure and system-scale regional energy planning. This combination of coordinated investments could also catalyze increased private investment in individual power generation assets, especially solar and wind.
- Financial institutions should promote system-scale studies to guide their assessment of risk and returns.
- While a major expansion of hydropower will trap sediment and exacerbate risks to the delta, the region confronts a range of challenges (e.g., groundwater pumping that contributes to subsidence and dikes, sluices and barrages that constrain sediment deposition) and thus a diverse set of interventions are required to maintain the resilience of the delta.
- Cambodia's 2019 dry season energy crisis spurred a group of renewable energy advocates to develop recommendations for how to rapidly promote the expansion of solar PV to help avoid future disruptions, which the government should explore. These include:
  * Fast tracking PPAs for solar and wind farms and preparing a standard template to ensure PPAs are "bankable";
  * Refining regulations to promote commercial and industrial rooftop solar;
  * Allowing Rural Energy Enterprises to incorporate solar into their grids; and
  * Stimulate investment in energy efficiency and establish policies to encourage efficient buildings and appliances.

If governments, partners and investors follow these recommendations, the Mekong region has the opportunity to secure a brighter energy future with low-carbon power systems that can reliably meet the needs of growing economies and maintain the productivity and diversity of one of the world's most incredible river systems.

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Chapter 8

CONCLUSIONS

Ola Jennersten / WWF-Sweden

Within a very short time, the vision of low-cost, low-carbon, and low-impact power systems has become a credible possibility. Much of the renewable energy revolution is already underway.

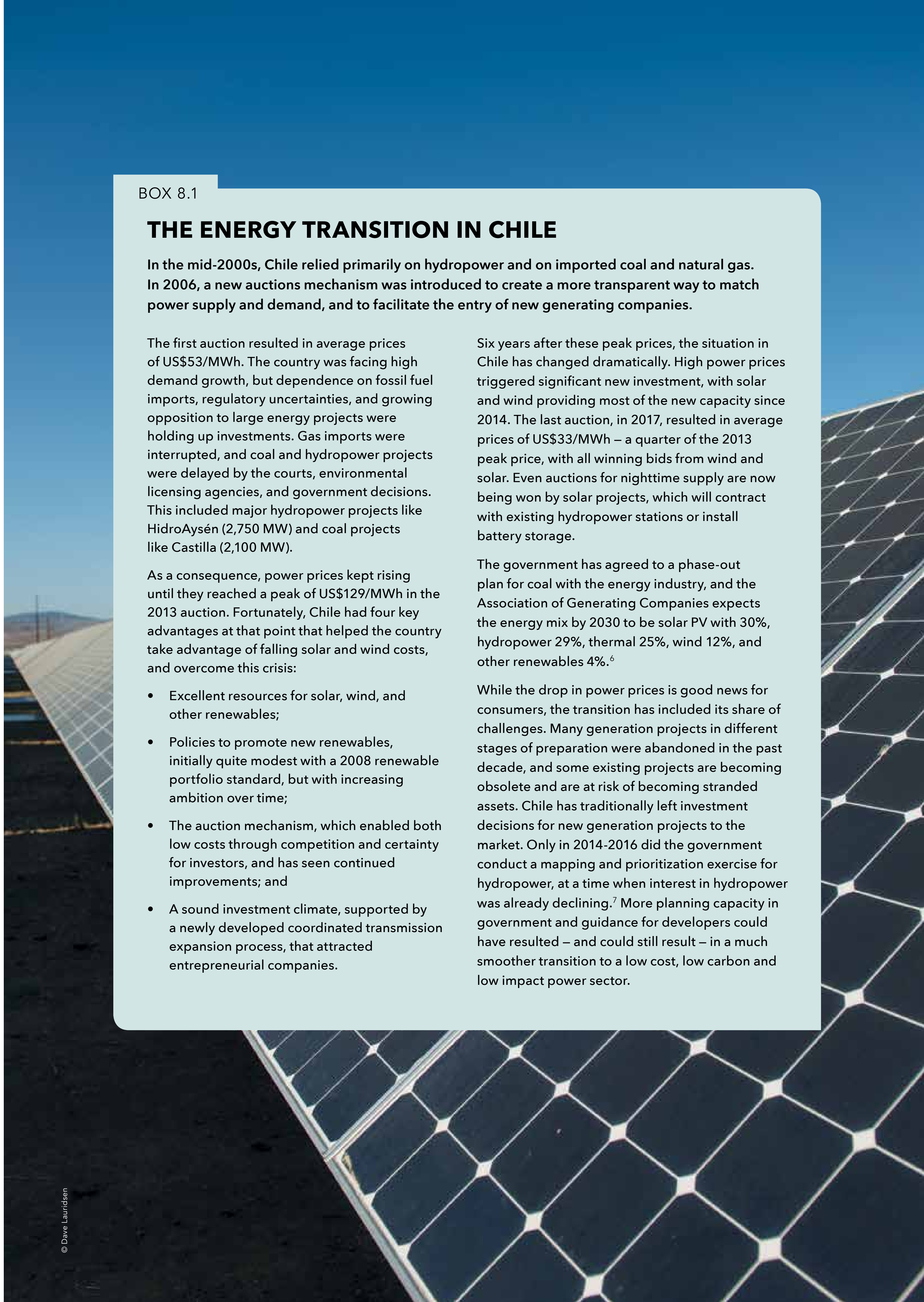
Although this transition received some initial momentum from policies — ranging from national renewable energy requirements and investments in research, to global climate commitments — it is now driven as much by technological innovation and marketplace competition as by policy[1].

Today it is possible to envision a future in which electricity systems are accessible, affordable and powering economies with a mix of renewable energy technologies — including solar, wind, storage and low-impact hydropower. This future will not require the dramatic tradeoffs of past development. Growing electricity demands and climate objectives can be achieved while avoiding the negative impacts on the world's remaining free-flowing rivers posed by high-impact hydropower, including the displacement of many communities, and the loss of productive freshwater fisheries and much of the sediment needed to keep economically crucial deltas above the rising seas.

While there is perhaps no single country that illustrates all components described in this report, many countries are leading the way on various elements of the renewables transition. Some, including Norway and Iceland, have already achieved close to 100% renewable power, but challenges remain to increase the broader sustainability of their generation fleet. Others, such as India, have used auctions that resulted in record-low costs for solar power to facilitate near-universal access to power. China's massive expansion of manufacturing and generating capacity for solar and wind created economies of scale, contributing to the global drop in costs of those technologies. Portugal is retrofitting its existing hydropower with pumped storage, and Thailand has committed to a major expansion of floating solar on its reservoirs. Many countries are moving forward on more systematic planning of their power systems, either to ensure that variable renewables are well integrated into reliable grids, and/or to ensure that their massive expansion does not produce a public backlash by identifying low-impact sites. And a number of planned high-impact hydropower dams have been suspended with development shifting toward options with lower impacts.

Costa Rica illustrates how a country with a grid that is already low carbon can diversify sources and further reduce the impacts of future expansion. The country's grid is currently 98% renewable with a carbon intensity of 0.08 tons/MWh[2] and leaders recently announced a goal of becoming carbon-neutral by 2021.[3] However, with a high proportion of generation from hydropower (75%), many of its rivers have already been dammed. The proposed El Diquís Hydroelectric Project (631 MW) would have fragmented the country's only remaining large, free-flowing river. Initially suspended in 2011 to allow consultation with indigenous groups about the dam's impacts, it was indefinitely suspended seven years later. Pointing to slowing demand due to energy efficiency and changing economic costs, the government concluded that the dam was no longer consistent with a least-cost expansion[4]. Future power expansion in Costa Rica will now feature solar, wind, and geothermal sources, while the country's significant existing fleet of hydropower plants will facilitate the expansion of these other sources. Meanwhile, consistent with Costa Rica's emphasis on environmental protection, its most recent hydropower project (Reventazón with 305 MW, completed in 2016) included as mitigation the protection of the nearby Parismina River as a free-flowing river.[5] Encompassing a low-carbon grid, formal protections for rivers, and future expansion of renewables facilitated by existing hydropower, Costa Rica is moving strongly toward a power system that is low cost, low carbon and low impact.

Dramatic transitions of a major economic sector, such as is now underway for electricity, nearly always present both challenges and unprecedented opportunities. Until a few years ago, Chile's power sector appeared to have few choices other than relying on large-scale traditional energy technologies, which were becoming increasingly difficult to build (Box 8.1). Chile has now managed to reduce power



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BOX 8.1

THE ENERGY TRANSITION IN CHILE

In the mid-2000s, Chile relied primarily on hydropower and on imported coal and natural gas. In 2006, a new auctions mechanism was introduced to create a more transparent way to match power supply and demand, and to facilitate the entry of new generating companies.

The first auction resulted in average prices of US$53/MWh. The country was facing high demand growth, but dependence on fossil fuel imports, regulatory uncertainties, and growing opposition to large energy projects were holding up investments. Gas imports were interrupted, and coal and hydropower projects were delayed by the courts, environmental licensing agencies, and government decisions. This included major hydropower projects like HidroAysén (2,750 MW) and coal projects like Castilla (2,100 MW).

As a consequence, power prices kept rising until they reached a peak of US$129/MWh in the 2013 auction. Fortunately, Chile had four key advantages at that point that helped the country take advantage of falling solar and wind costs, and overcome this crisis:

- Excellent resources for solar, wind, and other renewables;
- Policies to promote new renewables, initially quite modest with a 2008 renewable portfolio standard, but with increasing ambition over time;
- The auction mechanism, which enabled both low costs through competition and certainty for investors, and has seen continued improvements; and
- A sound investment climate, supported by a newly developed coordinated transmission expansion process, that attracted entrepreneurial companies.

Six years after these peak prices, the situation in Chile has changed dramatically. High power prices triggered significant new investment, with solar and wind providing most of the new capacity since 2014. The last auction, in 2017, resulted in average prices of US$33/MWh – a quarter of the 2013 peak price, with all winning bids from wind and solar. Even auctions for nighttime supply are now being won by solar projects, which will contract with existing hydropower stations or install battery storage.

The government has agreed to a phase-out plan for coal with the energy industry, and the Association of Generating Companies expects the energy mix by 2030 to be solar PV with 30%, hydropower 29%, thermal 25%, wind 12%, and other renewables 4%.[6]

While the drop in power prices is good news for consumers, the transition has included its share of challenges. Many generation projects in different stages of preparation were abandoned in the past decade, and some existing projects are becoming obsolete and are at risk of becoming stranded assets. Chile has traditionally left investment decisions for new generation projects to the market. Only in 2014-2016 did the government conduct a mapping and prioritization exercise for hydropower, at a time when interest in hydropower was already declining.[7] More planning capacity in government and guidance for developers could have resulted – and could still result – in a much smoother transition to a low cost, low carbon and low impact power sector.

costs drastically, while committing to phasing out coal and shifting away from new dams in undeveloped basins — allowing dozens of rivers to remain free-flowing — and toward solar, an expansion facilitated by its existing hydropower fleet. Chile will be able to showcase its success story at the 2019 UN Climate Conference in Santiago de Chile.

The example of Chile shows that lower solar and wind costs are necessary, but not sufficient by themselves. Smart policy and regulatory frameworks are still needed to speed up the transition, and to ensure that it is sustainable. And, in fact, the energy transition is not yet keeping pace with what is needed. IRENA estimates that renewables must reach 85% share of global generation capacity by 2050 to meet climate objectives, which will require a tripling of the rates of increase in new wind capacity and a doubling of the rates of increase of new solar PV capacity from recent years[8].

Achieving the vision will require policy, financial, and technical innovations across all countries. Fortunately, at this stage the feasibility of low-carbon, low-cost and low-impact systems — and the benefits of achieving them — are becoming clear, creating powerful incentives for different groups of stakeholders:

- Governments can (1) implement system-scale planning and licensing focused on integrated power systems to identify and develop those that are low cost, low carbon and low impact. Through this, countries can reassess plans for hydropower to factor in the full value of rivers and consider the availability of lower impact alternatives; and (2) create competitive frameworks to accelerate the renewable energy revolution to help them meet international commitments, most importantly national contributions to the Paris Agreement, SDGs, and CBD targets. Their citizens will benefit from low-cost electricity needed to improve living standards and drive economies. Further, countries will benefit from reduced pollution and healthier rivers and landscapes, while minimizing the social conflicts that can arise due to climate instability and opposition to projects.
- Developers can facilitate the transition by supporting more comprehensive upstream planning and by improving their own project assessments using sustainability protocols and safeguards. Developers will benefit from a pipeline of lower-risk projects and, specifically for the hydropower sector, from providing higher-value ancillary services.
- Financial institutions can also support more comprehensive planning as a way to develop a pipeline of lower-risk projects, focusing their lending on opportunities emerging from such plans, and requiring their clients to apply ambitious sustainability protocols and safeguards. Making direct funding available for such activities can be critical. Financiers will benefit from lower-risk projects and, particularly relevant for development banks, accomplish diverse objectives, including multiple SDGs.

Most importantly, the renewable revolution offers countries the chance, for the first time in history, to achieve universally affordable electricity supplies that no longer require people to be exposed to air pollution, resettlement, and the loss of livelihoods and traditional landscapes, including the diverse benefits of healthy rivers. Although countries no longer have to accept these losses as the regrettable-but-unavoidable trade-offs of economic growth, without proactive efforts, opportunities for more-sustainable power systems will continue to be missed. Transitioning to low-carbon, low-cost, and low-impact systems is not only a moral imperative, it is within our reach. It is up to all energy sector stakeholders to make it happen by working together to accelerate the renewable revolution.

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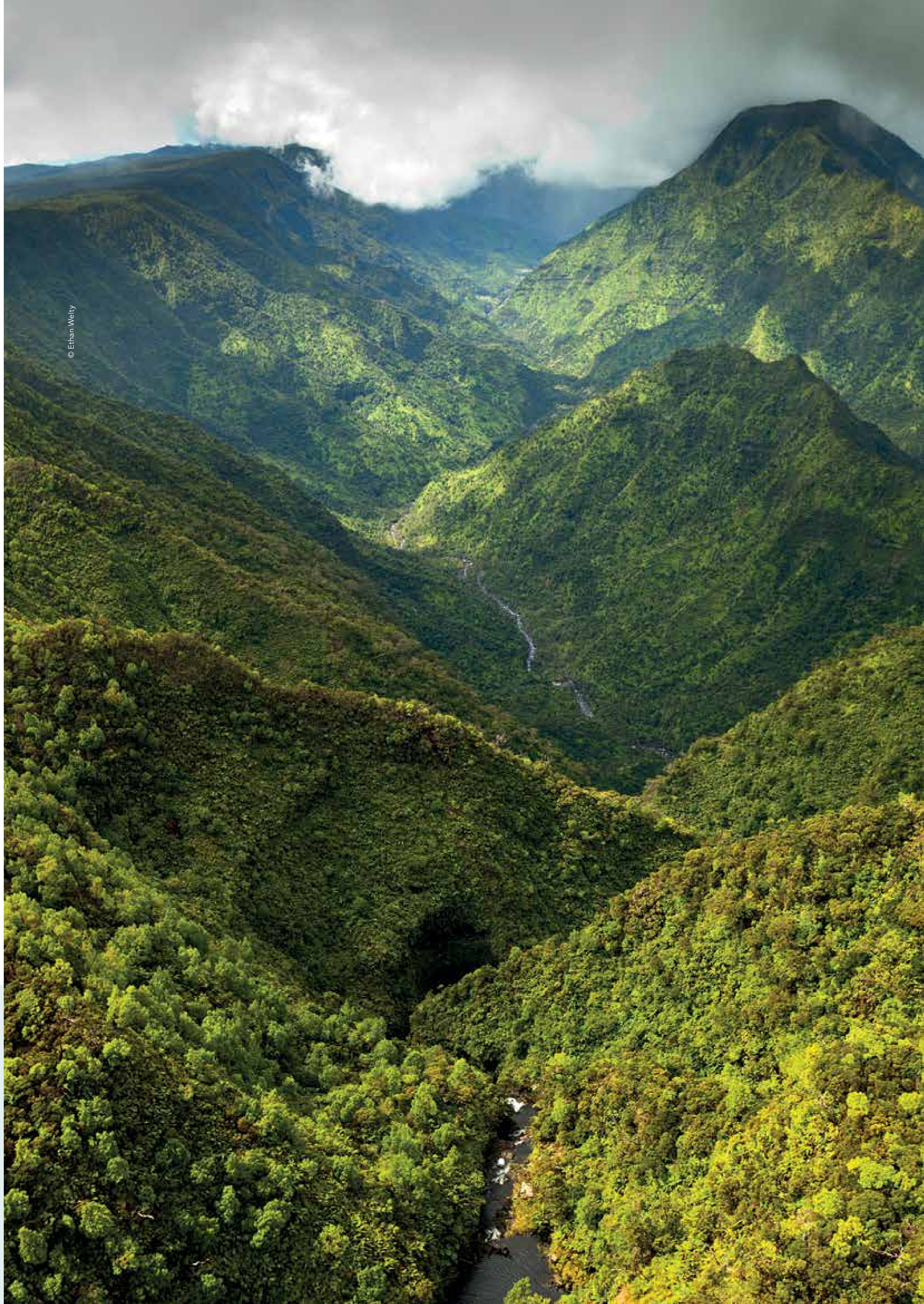

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Examples of Project Preparation Facilities with potential to finance early planning at system scale

Host Organization Planning Finance	Name of Facility	Areas of Involvement on Early
Climate Investment Funds	Clean Technology Fund (CTF)	Large-scale financial resources to invest in clean technology projects in developing countries, which contribute to the demonstration, deployment, and transfer of low-carbon technologies with a significant potential for long-term greenhouse gas emissions savings
Global Infrastructure Facility	n/a	Preliminary work to prioritize investments and test a project concept through "pre-feasibility" analysis; as well as support to legal, regulatory, or institutional reforms as required to enable successful development and/or participation of long-term private capital in the financial structure of a particular project
International Bank for Reconstruction and Development	Energy Sector Management Assistance Program (ESMAP)	Strategic support in market and regulatory reform, power system planning, and integration of regional infrastructure
	Public-Private Infrastructure Advisory Facility (PPIAF	Support the creation of a sound enabling environment for the provision of infrastructure services by the private sector
Inter-American Development Bank	INFRAfund	Creating enabling environments and building institutional capacity
	NDC Invest	Help public and private sector stakeholders to develop investment plans and programs to reflect today's and tomorrow's climate needs and circumstances
IDB Invest	Sustainable Infrastructure Program (SIP)	Accelerate sustainable infrastructure development in the region by catalyzing private sector investment for the implementation of the Nationally Determined Contributions (NDCs) of the Paris Agreement
Asian Development Bank	Asia Pacific Project Preparation Facility (AP3F)	Upstream sector reform work linked to potential projects that are being prepared or soon will be, including advising client countries on enabling reforms (such as legislation and regulation frameworks, and possible use of guarantees or incentive schemes), appropriate PPP project selection criteria, staff training, and market and/or stakeholder awareness
African Development Bank	Africa50 Project Development	Financing at earlier stages of projects, engaging with stakeholders along the deal cycle, with a particular focus on mobilizing political support
	NEPAD-Infrastructure Project Preparation Facility (NEPAD-IPPF)	Supports the development of regional and continental infrastructure to prepare high-quality viable transboundary projects in energy, transboundary water resources, transport and ICT.
European Bank for Reconstruction and Development	Infrastructure Project Preparation Facility (IPPF)	Project preparation, policy dialogue and institutional strengthening to address both public sector infrastructure projects as well as PPPs

Methods for spatial analyses

1. Potential solar generation on reservoirs (See box 7.1):

An estimate of the floating solar potential in the Mekong basin was calculated for all existing reservoirs. The methodology follows that used in the World Bank report[1] 'Where the Sun Meets Water: Floating Solar Market Report'. A dataset for existing reservoirs in the Mekong basin was developed by combining two sources: 1.) Global Reservoir and Dam (GRanD) database[2] and 2.) MRC (2012) and International Rivers (2014)[3]. In total, 44 reservoirs (from various types of dams, including irrigation, hydropower, multi-purpose dams) across 4 countries (Cambodia, Vietnam, Laos and Thailand) were identified in the Mekong basin with more than 2,000 km^2 of combined surface area.

Floating solar potential was calculated for three different proportions of reservoir surface area to be covered by solar panels:1%, 5%, and 10%. The potential peak capacity or nominal power was then derived by multiplying the surface area assumed available for solar panel modules by the efficiency levels of currently available PV modules (10%[4]).

The geographic coordinates of each reservoir's centroid were identified using a GIS[5]. The geographic coordinates of each reservoir were then uploaded in the PVGIS tool (Photovoltaic Geographic Informational System)[6] which estimates the average yearly energy production of a PV system connected to an electricity grid. The tool determines energy production based on solar radiation, temperature, wind speed and the type of PV module. The PVGIS tools assumes 14% loss of energy in the system in addition to losses that are calculated from temperature, irradiance and angle of incidence. Thus, for each level of surface area (1%, 5%, and 10%), the average annual energy generation potential (GWh) was estimated for each reservoir. The floating solar potential ranging from 1, 5 and 10% of reservoir surface area sums to 3,000, 14,900 and 29,800 respectively (Table A1).

2. Ratio of potential for low-impact wind and solar to generation from potential hydropower dams, by country (Figure 5.4)

We used a database of potential dams from Zarfl et al. (2015)[7] which provides information on the country and capacity of potential dams. We converted capacity to generation using a capacity factor of 0.36. We then summed generation by country and used country-level data from Baruch-Mordo et al. (2018)[8] to derive the ratio of generation potential from low-impact wind and solar to potential hydropower generation for each country.

ENDNOTES

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Table A1. Potential generation from floating solar PV in reservoirs of the Lower Mekong basin

Name	Reservoir surface area (km²)	Annual GWh 1% Area	5% Area	10% Area
Nam Ngum 1	369.4	510	2,549	5,098
Xelabam	0.6	1	4	8
Xeset 1	0.1	0	1	1
Theun-Hinboun	6.3	9	43	86
Nam Ngay	0.3	0	2	3
Nam Ngum 2	122.2	155	776	1,552
Nam Lik 1-2	24.4	34	170	339
Theun-Hinboun expansion	6.3	9	43	86
Theun-Hinboun exp. (NG8)	105.0	144	719	1,439
Plei Krong	53.3	75	373	746
Yali	64.5	88	439	877
Se San 3	3.4	5	24	47
Se San 3A	8.8	12	60	121
Se San 4	58.4	82	409	818
Se San 4A	1.8	2	12	25
Buon Tua Srah	37.1	49	243	486
Buon Kuop	5.6	8	38	76
Sre Pok 3	17.7	24	121	242
Sre Pok 4	3.8	5	26	51
Huai Kum	2.4	3	16	33
Pak Mun	60.0	86	432	864
Ubol Ratana	401.2	590	2,949	5,898
Lam Ta Khong P.S.	37.0	53	265	529
Nam Pung	15.8	23	115	229
Chulabhorn	7.0	10	49	99
Sirindhorn	235.5	344	1,719	3,438
Haixihai	4.0	6	28	56
Zibihe	7.9	11	53	107
Nam Oun	38.4	56	282	564
Nong Han Lake	73.2	107	534	1,069
Lam Pao	202.3	299	1,497	2,994
Lam Chang Han	4.8	7	36	71
Lamphraphloeng	9.6	13	67	134
Lamnangrong	11.6	17	84	167
Houayho	31.0	44	219	437
Total		**2,878.96**	**14,394.80**	**28,789.61**

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