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Building a Framework to Understand the Energy Needs of Adaptation

Marinella Davide [1,2,3,*], Enrica De Cian [1,2,3] and Alexis Bernigaud [2]

1 Department of Economics, Ca' Foscari University of Venice, 30123 Venice, Italy
2 Euro-Mediterranean Center on Climate Change, 30175 Venice, Italy
3 RFF-CMCC European Institute on Economics and the Environment, 30175 Venice, Italy
* Correspondence: marinella.davide@unive.it

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Abstract: Adaptation is a critical option to cope with climate change, as it alleviates the residual climate damages not avoided by emission reduction measures. However, adaptive actions can consume extra amounts of energy. This paper introduces a framework to identify the energy use associated with adaptation and qualifies its relevance in terms of sustainable development. A qualitative, bottom-up analysis of the policy commitments submitted in the context of the Paris Agreement and the 2030 UN Agenda for sustainable development is complemented with a review of the literature on adaptation, energy, and sustainable development. The analysis of the policy options related to vulnerability reduction in the Nationally Determined Contributions reveals a set of recurring adaptation strategies strongly associated with energy use. By linking the resulting options to the United Nations' Sustainable Development Goal (SDG) targets and indicators, we show that energy-related adaptation options are all connected to at least one SDG, though the strength of the connection varies across adaptation options and SDGs. The descriptive synthesis provided in this paper sets a framework for future research aimed at assessing the energy implications of adaptation strategies, contributing to further understand the nexus between climate policy and development.

Keywords: climate change; adaptation; energy; sustainable development

1. Introduction

The landmark climate deal adopted in 2015 at the 21st UNFCCC Conference of the Parties (COP 21) confirms the need for increased efforts to cope with the impacts of climate change [1]. For the first time in the history of climate negotiations, the Paris Agreement establishes a long-term adaptation goal, reiterating the necessity of an integrated approach to climate resilience and inclusive low-carbon development. Even if the rise in global average temperature is restricted within 2 °C, impacts of climate change are inevitable [2,3] with negative effects primarily in low-income countries located near the Equator [4] that have limited capacity to adapt [5].

In recent years, adaptation to climate change has emerged as a crucial area, not only in research, but also in national and subnational-level planning. The analysis of the best-suited options to anticipate and cope with adverse climate impacts has been complemented with an increased interest in opportunities connected with adaptation as well as on the interrelations between adaptation, mitigation, and alternative sustainable pathways [5]. The research community shares a broad consensus on socio-economic development being the foremost strategy to reduce vulnerability [6–9]. Being a key enabling component of development, energy can facilitate adaptation, but what are the energy implications of adaptation has not featured prominently in the literature. A recent conceptual systematic review defining energy services [10] sheds new light on the overlooked linkages between energy use and adaptation. Several energy services are noticeably climate sensitive and provide a critical margin of adaptation. Most of them have been gaining increased attention within the adaptation literature. Space heating and cooling allow households to maintain the desired levels of thermal comfort in their living environment, alleviating climate-related damages to health and improving wellbeing. In their estimates based on United States data, Deschenes and Greenstone [11] find that daily temperature increase due to climate change will lead to a 3% rise in the overall mortality rate by the end of the century, and to a consequent growth in annual residential energy consumption by 11% (see also Dell et al. [12] for a review of the empirical literature on climate-related impacts). The key role of residential Air Conditioning (AC) diffusion in reducing hot-day-related fatalities is demonstrated by Barreca et al. [13], which estimate a 70% decline in mortality during the 20th century because of household adaptation response through AC adoption. Moreover, cooling systems make commercial and industrial activities possible where already difficult climatic conditions negatively influence production and labor productivity. This is the case, for example, of Caribbean and Central American countries, where a short-term increase of 1 °C in surface temperature is associated with a consistent reduction (2.5%) in industrial economic output [14]. Similarly, in the U.S., an additional extremely hot day has been estimated to lower payroll per capita in non-agricultural production by 0.22% on average [15]. This implies that a year with annual temperatures 2 °C warmer than average is associated with a 4.56% reduction in per capita payroll for highly exposed sectors. Interestingly, a significant proportion of the differences in marginal impacts across U.S. counties can be explained by the spread of AC [15]. Beyond impacts on the labor force, other industrial activities are very sensitive to outdoor temperature, such as the food and vaccine cold-chain, as they require narrow stable temperature windows [16,17]. Future economic and population growth in the hottest areas of the world are expected to drive the share of space cooling in total electricity use in buildings up to 30% by 2050, with India, China, and Indonesia contributing to half of global cooling energy demand growth [18]. Increased temperature due to climate change will place further stress on the power system, unless strong energy efficiency measures are undertaken. In the water sector, desalination, water treatment, and distribution are all highly energy-intensive processes, and the energy-intensity of the entire water chain is likely to increase over time, as climate change will make water resources less accessible while treatment standards and demand rise [19,20]. Increased demand for water to deal with extreme droughts implies greater dependency on energy in both the agricultural and residential sectors [21]. In this regard, existing literature calls for clear definitions of water-sector boundaries and greater standardization of approaches to profiling energy use [19]. In the residential segment, for example, although energy requirements of end-use processes (e.g., water heating) carry a relevant portion of the environmental burden, they are generally overlooked because occurring outside the water industry [19,20]. In the agricultural sector, the expansion of irrigation necessary to meet increased demand for water will have a significant impact on energy consumption. Although with variations depending on depth or distance, pumping of groundwater is recognized to be the most energy-intensive process, consuming even 25% more energy than surface-water irrigation [19]. However, estimates usually consider only electricity use, with few examples assessing different energy sources (e.g., petrol or diesel). This prevents a clear understanding of carbon emissions embedded in the irrigation process and, consequently, the comparison with more efficient and clean-energy alternatives, as for example renewable energy-based islanded microgrids, which may represent a viable solution to power irrigation systems and rural electrification in emerging and developing economies [22]. Not only water requirements for agriculture will need more energy, cooling demand for livestock will also see an increase to protect animal comfort and production from the impacts of rising temperatures [21]. At the aggregate level, studies suggest that—by 2050—world's population could need up to 17% more energy in order to cope with a warmer climate across all sectors of the economy [23].

On closer inspection, many of the energy services that can contribute to reducing climate vulnerability largely overlap with the basic energy services to ensure minimum standards for decent living [24] related, for example, to adequate water supply or safe and comfortable space [25]. The literature has indeed emphasized the role of energy as key for decent living conditions [26], stressing the urgency to decarbonize the sources used to provide those services [27]. Recent studies have shown the strong interlinkages between energy and Sustainable Development Goals (SDGs), identifying energy system transformations as a crucial component of their realization [28–30]. However, even including SDG 13 on Climate Action and other adaptation-related SDG targets, this literature only partially addresses the linkages between energy and climate change adaptation. In particular, in analyzing the synergies and trade-offs between clean energy and climate change goals, McCollum et al. [28] primarily focus on the support of the former towards emission reduction objectives. The risk of increasing energy demand is recognized in connection with expanding water availability (SDG 6), as well as the potential benefits of best practices in reducing energy use in the agricultural sector (SDG 2) [28]. Similarly, among the 65 SDGs targets showing trade-offs with SDG 7 (clean energy), Fuso Nerini et al. [29] include challenges related to the food and water systems. Both trade-offs and synergies are identified in relation to infrastructure, as increased energy will be needed to power food systems, medical facilities, water treatment and distribution systems whereas reduced energy usage is expected from more efficient water infrastructure. A very recent study provides an interesting approach to quantitatively estimates the additional energy demand requirements (compared to business-as-usual) of SDG targets and indicators [30]. Authors quantify the increase in energy demand required to strengthen resilience and adaptive capacity related to disaster recovery. Their focus is, indeed, limited to the energy intensity of building post-disaster container houses. Further elements of adaptation emerge, however, from the analysis of other SDG targets. They find that the amount of additional energy required for providing clean water, food, and health care access is relatively small compared to the requirements of other objectives (e.g., access to education). In the agricultural sector, the amount of energy saving related to sustainable practices will be higher than the increase in energy required to support small farmers' productivity.

Overall, these studies represent an important effort toward the understanding of the relation between energy and the different dimensions of development. They also contribute to showing that many adaptation actions are strongly interconnected with development priorities. Yet, the energy use and the Greenhouse Gas (GHG) emission implications of adaptation remain underexplored, with research efforts limited to sector-specific analyses [19,31,32]. This is confirmed by the recently published IPCC 1.5 report [33], which recognizes that the literature on the expected impacts of adaptation on sustainable development is scarce, especially when considering energy requirements as the channel of interaction (e.g., tradeoffs between improving health benefits and using air conditioning). As the scale of adaptation needs to expand, the associated increase in energy could lead to more emissions and higher energy prices, with potentially negative consequences for poor households and economic competitiveness, fueling a potentially negative feedback loop on sustainable development.

But for a few exceptions [18], socio-economic and climate policy scenarios still do not integrate energy needs for adaptation [34]. A prominent example emerging from the literature is space cooling. CO2 emissions from cooling have seen a threefold increase since 1990, for a cumulative amount equivalent to the total emissions of Japan. At present, space cooling account for 10% of total electricity demand and for the 12% of the CO2 emissions of this sector [18]. Whether energy use connected to adaptation could support progress towards sustainability has not been explicitly addressed. On the one hand, the energy services that might become more needed under the pressure of climate change—such as space cooling, water availability, and food and vaccine cold-chains—support the achievement of several Sustainable Development Goals (SDGs) [35]. On the other hand, if not properly managed, additional climate-induced energy needs can lock our societies into energy-intensive infrastructure [36], making decarbonization and the achievement of Goal 13 on Climate Action more difficult.

In this paper, we investigate to what extent the adaptation plans proposed in the context of the Paris Agreement are associated with energy use and explore the implications for sustainable development. Starting from the definition of energy for adaptation as those functions and actions that reduce climate vulnerability and most directly influence energy demand, we scrutinize the Nationally Determined Contributions (NDCs) submitted to the UNFCCC to identify the high-priority adaptation options most directly connected to energy use. This approach makes it possible to identify a comprehensive set of adaptation measures and understand the extent countries plan to rely on each of them. After validating the selected options within the adaptation literature, we investigate how energy for adaptation contributes to achieve the 17 SDGs. We adopt a wider notion of energy use for adaptation that goes beyond cooling and air conditioning, including energy services that are climate sensitive and provide benefits in terms of reduced vulnerability across all sectors. The overarching goal of this paper is to introduce and define the concept of energy use for adaptation and qualify its relevance in terms of sustainable development. It is intended to provide a set-up for framing the future research aimed at quantifying the energy requirements of adaptation. The remainder of the paper is organized as follows. Section 2 describes our methodology. Section 3 discusses the results. Section 4 concludes and outlines the implications of our findings for future research.

2. Materials and Methods

The NDCs offer a unique set of documents revealing national interests and preferences regarding climate action [37]. While governments often avoid making their preferences clear, the bottom-up nature of the contributions submitted under the Paris Agreement make it possible to understand countries' plans and priorities. Among the 190+ national governments that submitted an INDC or a NDC to the UNFCCC, henceforth (I)NDC, nearly 90% of them include adaptation [38,39]. They are predominantly emerging and developing countries, where the priority of protecting their people from dangerous climate impacts is more urgent. However, the analysis of (I)NDC's contents on adaptation remains limited, mainly because of the challenges in defining and tracking adaptation actions [40]. We therefore rely on the original sources of (I)NDC provided by the UNFCCC, in order to identify those contributions, including an adaptation component and the extent to which planned actions could entail significant use of energy [41,42].

We identify and analyze 138 (I)NDC documents including adaptation objectives and plans, from which we select actions that most directly affect energy use while reducing vulnerability. We examine both unconditional and conditional pledges, paying particular attention to the context as well as to all sections (e.g., capacity buildings, technology transfer, fairness, and ambition), keeping track of whether a specific option is mentioned as adaptation, mitigation, or both (see Figure 1 and Supplementary Materials). This makes it possible to observe the different country perspectives on a given option and to identify the adaptation actions that can entail co-benefits for mitigation. For example, Togo features conservation of rainwater and reuse of wastewater among the adaptation priorities, while Madagascar mentions it in the mitigation section, because the emphasis is on biogas collection from wastewater treatment plants. Lebanon describes the reuse of wastewater in the adaptation section, but it also acknowledges the mitigation co-benefits.

We define energy use for adaptation as those adaptation strategies that most directly affect energy use according to any of the following four criteria:

1. Are energy-intensive or relate to energy-intensive sectors
2. Are a precondition for access to basic energy services
3. Require access to energy in order to spread their benefits and reach targeted population
4. Can save energy, directly or indirectly

These criteria clarify how energy relates to the adaptation options proposed by countries. The first criterion captures adaptation measures that involve sectors traditionally considered energy intensive (e.g., large-scale infrastructure) or that require a relatively higher amount of energy in their process compared to technologies used for similar purposes (e.g., multi-purpose dams as an energy-intensive hydraulic infrastructure and seawater desalination as one of the most energy demanding water treatment technology). The second criterion includes those options that aim at providing or extending access to basic energy services, such as renewable energy and electrification. The third criterion refers to those services that, independently from the energy sources and consumption levels, require access to energy to improve a certain outcome or to reach targeted populations (e.g., increasing irrigation or providing water heating as well as early warning systems, which require information and communication technology such as TV and mobile phones to reach individuals). The fourth criterion covers the adaptation options that can decrease the use of energy directly (e.g., thermal insulation) or indirectly, by stimulating behavioral changes or decreasing the amount of other resources, such as practices augmenting energy or water efficiency and conservation in both residential and agriculture sectors (e.g., education, efficient irrigation techniques).

On a broader perspective, these criteria allow us to group the adaptation measures into two major categories reflecting their potential impact on future energy use:

(a) Potentially energy-increasing (E-I) options, whose diffusion will result in an increase in the use of energy, including renewable sources.
(b) Potentially energy-saving (E-S) options, whose implementation will decrease energy demand.

The final list of options includes only those that (i) are mentioned as adaptation by at least one country and (ii) are found in the adaptation literature [31,43–47]. For example, decentralized renewable energy or energy efficiency are mostly proposed in the mitigation section, but several countries mention those strategies also in relation to adaptation and their importance in coping with climate impacts is acknowledged within the adaptation literature [21,31].

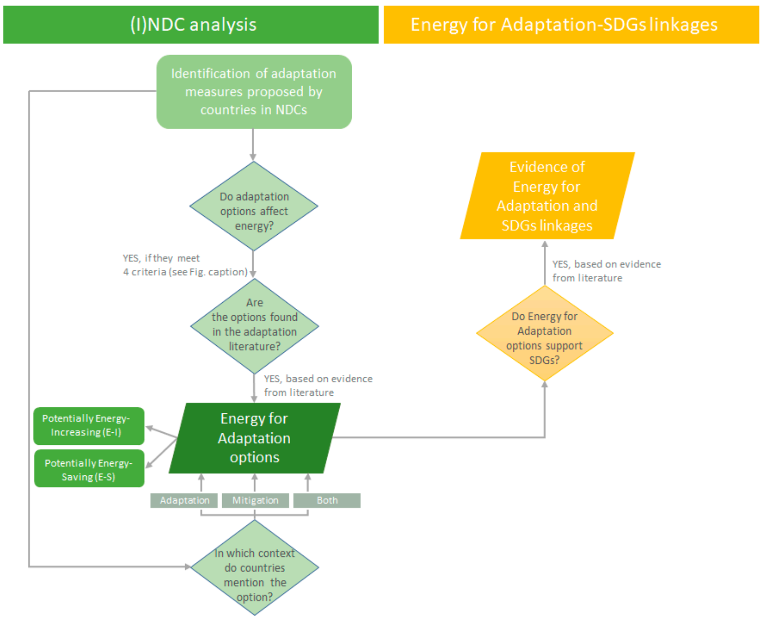

Figure 1. Flowchart of the research methodology. Green color shows the research steps related to the analysis of (I)NDCs and leading to the identification of the Energy for Adaptation options. The four criteria used in the first decision (Diamond shape n.1) are: (1) options are energy-intensive/relate to energy-intensive sectors; (2) options are a precondition for access to basic energy services; (3) options require access to energy to spread their benefits and reach targeted population; (4) options can save energy. The research phase on Energy for Adaptation linkages with SDGs is shown in yellow.

Building on an extended review of the literature carried out by the authors in this paper (Appendix A and Supplementary Materials), we associate each of the energy for adaptation options identified to the targets or indicators of the 17 SDGs to which it contributes. We focus on synergies (i.e., positive linkages) as the objective of the analysis is to bring evidence on how specific adaptation options to climate change contribute to sustainable development. We also consider the grey literature, as the topic is dominated by intense research and reporting activity carried out by international organizations as well as non-governmental and governmental agencies. To avoid double counting, within each SDG we uniquely map each adaptation option to the most strongly related indicator or target. Goal 13 on climate change is the exception, as all options contribute to the goal by definition. Indicators and targets are not always consistent with one another. We therefore alternatively use SDG indicators or targets on a case-by-case basis, based on the strength of the linkage (see Supplementary Materials). Because of the great variety of targets proposed in the SDG framework, we specify whether the identified options will be implemented using renewable energy sources. Figure 1 provides an overview of the key research steps. The flowcharts in green explains the analysis of (I)NDCs, the part in yellow relates to the Energy for Adaptation options-SDGs linkages.

3. Results

3.1. Evidence of Energy Use for Adaptation in the (I)NDCs

Energy use for adaptation emerges as consisting of 20 strategies most prominently mentioned to reduce vulnerability across all sectors of the economy. Table 1 lists the adaptation strategies proposed in the (I)NDCs that meet the four criteria outlined in the previous section along with the supporting literature. Examples of how those options are described in the national documents illustrate the degree of uncertainty related to actual implementation. There are countries with quantitative objectives, such as Antigua and Barbuda, which plans to increase seawater desalination capacity by 50% based on 2015 levels and to raise to 100% the share of electricity demand in the water sector and other essential services to be met through off-grid renewable sources. Seychelles plans to promote solar water heating among households and services, with a target of 80% by 2035. Co-generation in hotels is planned to cover 20% of hot water needs by 2035. Other countries are very specific about the technology to be used. Singapore plans to use advanced membrane technologies to treat high-grade, reclaimed water and make it safe to drink. There are then examples characterized by a higher degree of uncertainty. For example, Togo mentions the reuse of wastewater without any further details. Many among less developed countries—including Malawi, Zambia, and Lebanon—plan to increase the use of irrigation methods or the land area under irrigation. Depending on the efficiency of the irrigation systems implemented, the implications of these actions in terms of water and energy needs can vary. Among the adaptation challenges in the residential sector, Lebanon vaguely mentions the need for the national electricity infrastructure to deal with the augmented demand for cooling as air temperature will increase. Moldova, on the contrary, plans to support research on building management technologies able to save cooling energy and reduce the impact of global warming on energy demand. Several countries refer to broad programs such as Solar Homes (Bangladesh) or Sustainable Energy for All (Saint Lucia), which can be expected to bring benefits in terms of cleaner energy for living conditions.

Table 1. Overview of energy use for adaptation options from the (I)NDCs. The table describes the options, summarizes the supporting adaptation literature, and illustrates examples of how those options are mentioned in the (I)NDCs.

Sector	Adaptation Option	Description and Supporting Literature	Examples from (I)NDCs *
Water	Desalination	Removing salt from sea or brackish water can increase water supply [44,48]. Renewable-based technologies have a growing potential for this type of energy-intensive water treatment [49].	SINGAPORE: Expand desalination capacity to meet up to 80% of its water demand in 2060. ANTIGUA&BARBUDA: Increase seawater desalination capacity by 50% above 2015 levels by 2050. TUNISIA: Install mini seawater desalination plants using renewable energies in the tourist sector.
	Irrigation	Expanding equipped but not irrigated land as well as developing new irrigation projects [31,45] can reduce crop vulnerability. Large-scale deployment of solar pumps can support renewable-based irrigation [50].	ZAMBIA: Introduce water technologies for irrigation. MALAWI: Increase irrigation at smallholder level and increase the land area under irrigation. UGANDA: Expand the use of off-grid solar systems to support value addition and irrigation.
	Water distribution	Expanding or improving water supply and distribution, including water pumping can increase water supply and reduce losses. Given the high energy-intensity of this option, the use of renewable energy reduces the risk of maladaptation [20,45].	ANTIGUA&BARBUDA: 100% of electricity demand in the water sector through off-grid renewable sources. UGANDA: Extend electricity or expand use of off-grid solar system to support water supply. GAMBIA: Use of renewable energy for lifting water from wells and boreholes.
	Water conservation & improved efficiency	Implementing (i) agricultural practices that reduce water requirements; (ii) institutional changes that favor water-saving behaviors (e.g., water metering, changes in water charging and trade); (iii) improved water resource management and efficiency in industry and distribution [44,45] can reduce water needs, while keeping the same services.	JORDAN: Introduce water metering. IRAQ: Water use efficiency in distribution network and water consumption meters. SWAZILAND: Reduce vulnerability to the impacts of climate change through integrated water resource management.
	Water recycling and reuse	Implementing technologies to collect, reuse, and treat wastewater can increase water supply for non-drinkable uses, such as irrigation and industrial usages, as well as for domestic use [44,45].	TOGO: Reuse of wastewater. SINGAPORE: Use advanced membrane technologies to purify reclaimed, treated water, making water safe to drink. SWAZILAND: Water recycling and reuse.
	Water harvesting and groundwater recharge	Collecting and storing rainwater, artificially recharging groundwater aquifers, as well as implementing large-scale or small-scale water reservoirs on farmland can increase water supply and storage [44,45].	JORDAN: Maintenance of old Romanian wells for water harvesting purposes and establishment of new wells in the rural area. MOROCCO: Artificial replenishment of groundwater tables. LEBANON: Artificial recharge of groundwater aquifers and increasing surface storage.
	Efficiency in irrigation	Implementing water saving irrigation techniques (e.g., modern pressurized irrigation systems, micro-irrigation, wetting and drying practice) can reduce water and energy demand while keeping agricultural productivity [44,45].	CHINA: Develop water-saving agricultural irrigation. JORDAN: Introduce water saving technologies such as drip, micro-spray, and night irrigation. TOGO: Build and/or improve reservoirs for micro-irrigation and livestock watering in rural areas throughout all regions.

Table 1. *Cont.*

Sector	Adaptation Option	Description and Supporting Literature	Examples from (I)NDCs *
Living Conditions	Heating/cooling	Expanding space heating and cooling can increase resilience of the built environment [31,36,51]. Renewable-based heating and cooling have a large potential in several countries [52]. Smart building management systems can decrease vulnerability of energy infrastructure during peak electricity demand and increase occupants' wellbeing [18,53].	JORDAN: Expand the use of solar cooling in commercial and industrial facilities. MOLDOVA: Research on technologies and practices that save cooling energy and reduce electrical peak load. LESOTHO: Diffuse the use of efficient biomass space heating stoves.
	Water heating	Expanding water heating can increase resilience of the built environment [21]. Solar water heating has a large potential in many countries [31,52].	BANGLADESH: Expand Solar Homes Program. URUGUAY: Use of solar collectors for domestic hot water in large users, industrial and residential users. SEYCHELLES: Promote the use of solar water heating and cogeneration for hot water in hotels.
	Building standards	Implementing building codes, upgrading informal settlements, and retrofitting existing housing stock can reduce vulnerability of settlements and support mitigation [31,36,51].	MALAWI: Develop and implement climate related building codes to account for climate change. ANTIGUA&BARBUDA: By 2020, update the Building Code to meet projected impacts of climate change. URUGUAY: Green Seal Certification to achieve a more resilient performance of buildings, through appropriate design and materials.
Food	Livestock	Expanding heating and cooling services can increase the resilience of livestock and mitigate their vulnerability to water scarcity, drought, and extreme events [21].	MEXICO: Strengthen thermal comfort for livestock. JORDAN: Promote renewable energy in agricultural and food production for cooling and heating purposes (poultry production). MOLDOVA: Improve ventilation and air conditioning systems in livestock farms.
	Food storage	Building and upgrading storage facilities and processes can reduce post-harvest losses happening during the storage phase [54,55].	ETHIOPIA: Implement methods that prevent deterioration of food and feed in storage facilities. UGANDA: Expand post-harvest handling and storage. GAMBIA: Post harvest and food processing and preservation techniques.
Health	Medical services	Improving hospitals and infrastructure for medical services, expanding the network of health centers can increase the supply of the essential health services needed to reduce vulnerability of the health sector [56].	MALAWI: Construct more health centers in order to improve access to health facilities within a walking distance. SUDAN: Improve community sanitation and medical services, including capacities for diagnosis and treatment. SOUTH SUDAN: Public health systems strengthened by building hospitals.
	Early warning systems	Developing early warning systems can prevent human and economic losses in case of extreme events. Benefits can significantly exceed the costs, resulting in potentially large health benefits at low cost [45,57].	JORDAN: EWS to protect health from the potential impacts of climate change. MALDIVES: Develop appropriate early warning systems. BAHAMAS: Ensure that national emergency management plans also include heat stress

Table 1. *Cont.*

Sector	Adaptation Option	Description and Supporting Literature	Examples from (I)NDCs *
Infrastructure	Multi-purpose dams	Implementing dams that include more than one function can accommodate multiple adaptation needs, such as energy, water storage, and flood control [44,45].	MALAWI: Construct storage dams for hydropower generation. CENTRAL AFRICAN REPUBLIC: Develop hydroelectric installations (including micro-dams). JORDAN: Dams for storing floodwaters during the wet winter seasons and releasing water during the summer seasons.
	Rural electrification	Extending rural electrification can enable adaptation and mitigate climate vulnerability [47,58]. If based on a diversified network of energy sources, it can reduce the vulnerability of energy supply [31].	BANGLADESH: Key areas to address adverse impacts of climate change include Increased Rural Electrification. SAINT LUCIA: Sustainable energy for all initiative. UGANDA: Extend electricity to the rural areas.
	Transport	Improving the resilience of public transportation systems can reduce the vulnerability of urban centers, which are highly dependent on transport for daily functioning [51]. Improvements in vehicles and transport efficiency can compensate for the increased use of air conditioning [21,31].	SINGAPORE: Constant review and revision of design codes, regulations and policies to account for new information and the latest climate projections. BAHRAIN: Improve public transport efficiency, reduce personal vehicle use. MOLDOVA: Promote the use of heat-tolerant streets and highway landscape protection.
Energy Efficiency	Energy efficiency	Implementing energy efficiency programs can reduce the vulnerability of the energy system, with mitigation co-benefits. If less energy is required for an identical service, power outages will cause less damage and thus encourage climate resilience [21,31].	MALAWI: Promote the use of energy efficient light bulbs. SWAZILAND: Reduced vulnerability to climate change through energy efficiency. BURKINA FASO: Promote energy efficiency in urban and rural households.
Renewable Energy	Renewable energy	Differentiating the sources of energy supply by relying on a wider range of renewable sources can reduce the vulnerability of the energy sector [21,57]. For example, micro grids and decentralized energy solutions are low-carbon and create a more resilient power system [47].	ETHIOPIA: Expand electric power generation from geothermal, wind, and solar sources to minimize the adverse effects of droughts on hydroelectricity. EGYPT: Increased use of renewable energy may provide several opportunities, including reduced local environmental and health impacts. BURKINA FASO: Diversification of energy sources (solar, wind, biogas).
Information & Education	Information and education	Education, awareness and capacity building can enhance adaptive capacity and support development [47]. Climate services are an important component of the adaptation agenda [59].	KENYA: Enhance education, training, public awareness, participation and access to information on climate change adaptation across public and private sectors. Enhance climate information services. MALDIVES: Improve climate data collection, management and forecasting. Education, training, and public awareness remain a key priority.

* Authors' elaboration from the (I)NDCs textual analysis based on UNFCCC sources [41,42].

Overall, the energy-related adaptation options emerging from the (I)NDCs can be grouped into eight major sectors: water, infrastructure, renewable energy, energy efficiency, health, living conditions, information and education, and food. Figure 2 (and Supplementary Materials) reports the number of times (frequency) each energy for adaptation option is found in the (I)NDCs, grouped by sector. About one-third of the 988 energy for adaptation measures totally identified across 138 countries are related to the water supply sector, followed by infrastructure, which includes the provision of basic public services like electricity and transport. Renewable energy sources and energy efficiency measures, each accounting for 12% of total options, play a critical role as key solutions bridging mitigation and adaptation needs. Health services are often mentioned (10% of total number of options) as a sector that urgently needs to be extended and improved to respond to extreme weather events and potential climate change implications for human wellbeing. A similar share (10%) of adaptation actions contributes to ensure adequate life and working conditions (space heating and cooling, water heating, building codes). Enhanced information and education represent 8% of identified measures. A smaller share (4%) of adaptation actions requires energy services that contribute to the protection of vulnerable livestock (e.g., thermal comfort for livestock) and food supply (food storage). As expected, options related to infrastructure, renewables, and energy efficiency are mostly mentioned in relation to mitigation (shown in yellow in Figure 2), but they are sometimes perceived as having the potential to bring about co-benefits in terms of reduced vulnerability and improved resilience (Table 1). For example, decentralized energy systems based on diverse sources of energy—which are being accounted for in the renewable energy category—might be more flexible and less prone to power outages. To the extent that renewables help to enrich the portfolio of energy sources, they contribute to adaptation [31].

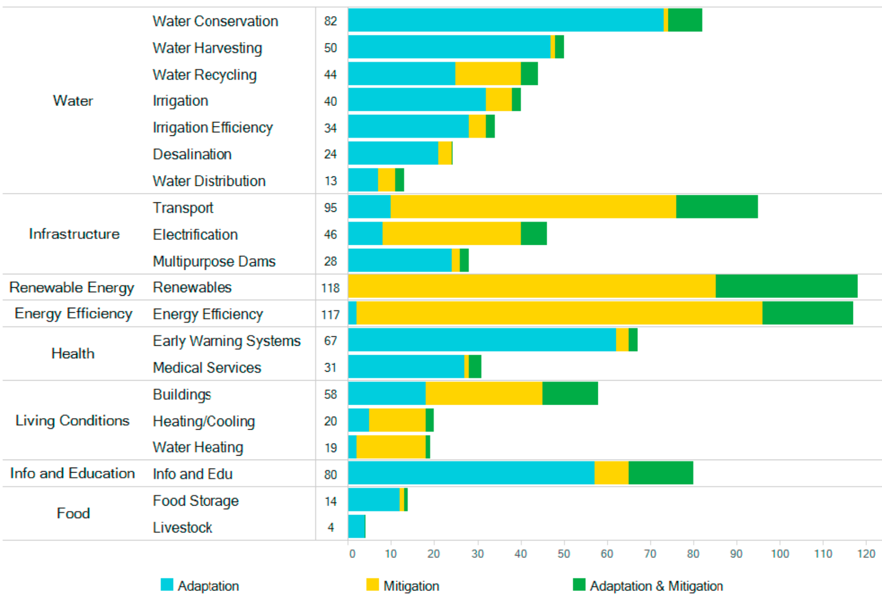

Figure 2. Frequency of energy for adaptation options in the (I)NDCs. Color scale shows whether options are mentioned as adaptation (blue), mitigation (yellow), or both (green). Numbers indicate the frequency of each of the 20 options shown in the bar chart.

Of the 20 energy-related adaptation options identified, 6 have a higher potential to save energy (water conservation and improved efficiency, water harvesting and groundwater recharge, efficiency in irrigation, building standards, energy efficiency, and information and education) while the remaining 14 can be considered energy-increasing (desalination, irrigation, water distribution, water recycling and reuse, heating/cooling, water heating, livestock, food storage, medical services, rural electrification, multi-purpose dams, transport, renewable energy, and early warning systems). The total count of the identified options, grouped by the expected direction of impact on energy demand (energy-increasing or energy-saving) is shown in Figure 3. Potentially energy-saving options, which account for 43% of total measures identified, can be viewed as adaptation options with mitigation co-benefits. On the contrary, the energy-increasing adaptation options may imply potential trade-offs between mitigation and adaptation objectives, if the energy source does not come from renewable energy. The distribution of sectors along these categories (color scale in Figure 3) shows that the highest energy saving potential, excluding measures directly addressing energy efficiency, is within the water and living condition sectors, where, potentially energy saving options represent more than 50% of the adaptation strategies. All the other sectors suggest a careful evaluation of the energy sources to be used, in order not to induce maladaptation.

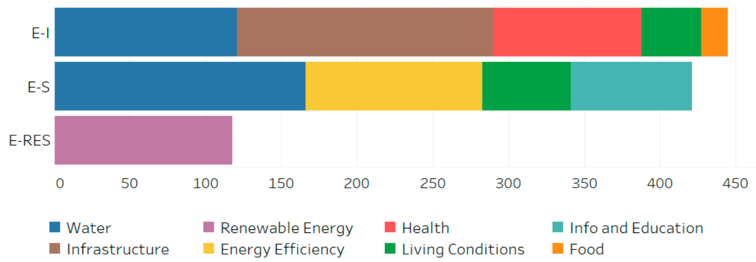

Figure 3. Frequency of energy for adaptation options by type of potential impact on energy use, energy-saving (E-S) and energy-increasing (E-I). Renewable energy is shown separately (E-RES).

The map in Figure 4 illustrates the geographic distribution of the total number of identified options by country, with details on the countries proposing the largest number of energy for adaptation options. The 138 countries that include adaptation plans are predominantly emerging or developing countries, though no pattern is identified between latitude and number of options. A rich list of energy-related adaptation options can be found in Jordan (18 options), Morocco (15 options), Uruguay (15 options), and Moldova (14). With respect to the potential impact on energy use, all countries with the largest number of options rely predominantly on energy-increasing options, with the exception of the water sector, where energy-saving options prevail (except in Yemen). Uruguay, Seychelles, Yemen, and Jordan have a relatively higher share of potentially energy-increasing strategies in the living conditions sector mostly due to heating/cooling and water heating.

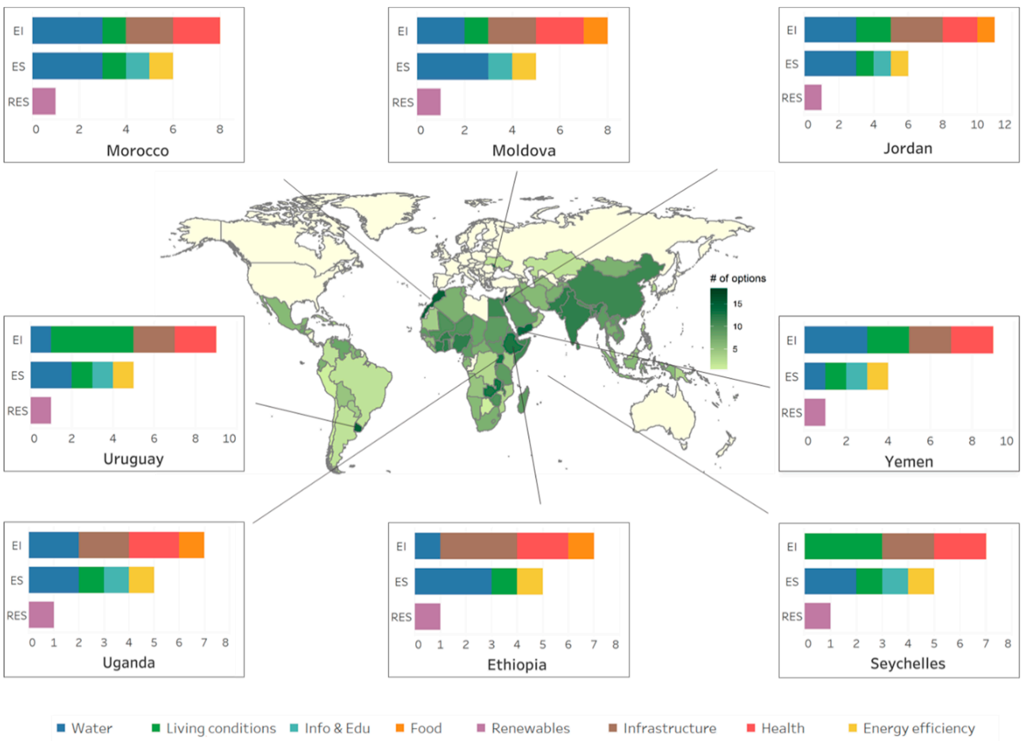

Figure 4. Geographic distribution of energy for adaptation options. Countries in light yellow do not include adaptation options in the (I)NDCs. Bar charts show the frequency of energy for adaptation options by type, energy-saving (E-S) and energy-increasing (E-I), in the top eight countries.

Among emerging economies, whose share in terms of carbon emission from the energy sector will be relevant in the near future, India and China propose respectively 12 and 11 energy-related adaptation actions. The proportion between potentially energy-saving and energy-increasing options results balanced in India, with 50% of the pledged adaptation actions connected to energy intensive sectors, including multi-purpose dams and transport, and extended energy services such as electrification, heating/cooling, and medical services. Conversely, China's (I)NDC shows a preference for energy-saving and renewable options that together account for 64% of the proposed energy-related adaptation measures. Fewer options emerge from the (I)NDC of Brazil (2), South Africa (8) and Mexico (9), with an overall predominance of energy-intensive adaptation actions primarily supported by the high number of E-I adaptation measures proposed by the central American country (90%). Details about all 138 countries analyzed can be found in the Supplementary Materials.

3.2. Evidence of How Adaptation Contributes to Sustainable Development

The energy-related adaptation options summarized in Table 1 are all connected to at least one SDG. The linkages between options and the SDGs are reported in Figure 5, which graphically shows them both in term of relevance (number of connections) and width (number of countries proposing the specific option). Based on the extensive review of the literature summarized in Table A1 and in the Supplementary Materials, the options that support the highest number of goals include renewable energy (contributing to 15 SDGs out of 17), rural electrification (showing synergies with 14 SDGs), and energy efficiency (relating to 13 SDGs). Water conservation and water harvesting follow, with nine linkages each. As an enabling condition of sustainable development, increased use of modern, efficient and clean energy sources plays a critical role in the realization of most SDGs, especially those most directly related to basic needs (e.g., education, health, food, water, gender equality) or economic growth and productivity (e.g., poverty alleviation, inequality, employment), reinforcing the findings of recent studies linking energy and SDGs [28–30].

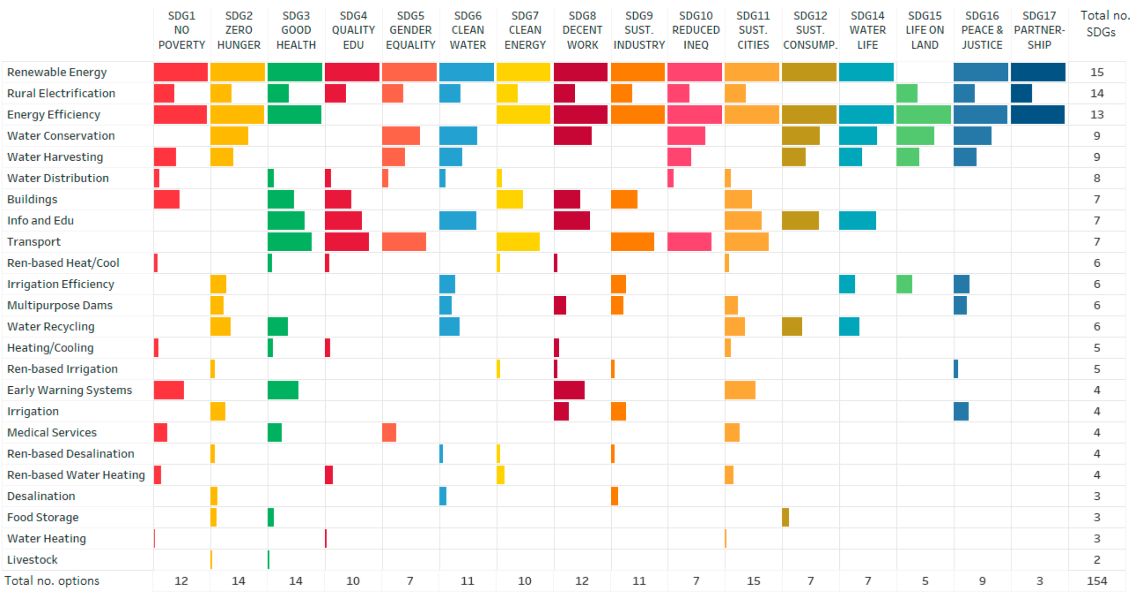

Figure 5. Contribution of energy for adaptation options to the SDGs. Colored bars for each option-SDG combination indicate a positive contribution of the option to the SDG. The size of the bar is proportional to the number of countries mentioning the option in the (I)NDC. Figures at the bottom summarize the numbers of options supporting each goal. Figures on the right summarize the numbers of goals supported by each option. All options, by definition, contribute to the climate action Goal 13 (not shown).

Concerning the energy implications of the five adaptation options that most strongly support sustainable development, expanding renewables and rural electrification are both energy-increasing, whereas energy efficiency, water conservation, and water harvesting are energy-saving. Although in several cases, the expansion of rural electrification is based on renewable sources (e.g., India mentions programs for rural electrification based on a decentralized renewable energy system), fossil fuels are still mentioned in some (I)NDCs.

Looking at the SDGs that would benefit the most from the implementation of the adaptation options highlighted, SDG11 (sustainable cities and communities) shows the greatest number of linkages with 15 (62% of all options) energy-related adaptation options supporting the achievement of this goal, followed by SDG3 (good health and well-being) and SDG2 (zero hunger), with 14 (54%) options each. SDG11 is supported primarily by adaptation solutions related to the infrastructure sector, including renewable energy, low-carbon, and climate-proof transport systems, as explicitly required by most of the targets and indicators included in the goal. SDG2 shows strong connections not only with the adaptation actions directly addressing the vulnerability of the food sector, but also with a high number of options related to water and energy sectors. Access to more efficient and cleaner energy technologies and practices that increase water supply and efficiency are key to sustaining food productivity and reducing post-harvest losses [54,55,60,61]. A greater heterogeneity characterizes the options that support SDG3, highlighting how options across all the sectors shown in Figure 2 contribute to the six targets in which the goal is articulated. Ensuring universal health will indeed benefit from medical services enhanced to protect vulnerable people from climate risks, increased food security and water quality, improved residential conditions due to building standards, deployment of cleaner and efficient appliances, as well as from educational campaigns targeting climate-sensitive diseases. Recent studies [62] highlight how building characteristics in the broad sense (from resilience affecting the sense of security to water quality, indoor pollution, thermal comfort, disinfection systems) indirectly and directly influence mental health and well-being. Numerous linkages also emerge with those goals involving sectors explicitly requiring the implementation or expansion of the energy for adaptation options, such as SDG7 (affordable and clean energy), supported by 10 options (42%), SDG6 (clean water and sanitation), supported by 11 options (45%). Table A1 describes in detail the mechanisms that give rise to the highlighted synergies for all options and all SDGs.

Whereas some options that most contribute to SDGs are widely proposed across (I)NDCs, such as energy efficiency and renewable energy, other options which also have a high potential to contribute to development, namely renewable-based water distribution, water conservation or water harvesting, are less frequently mentioned. By synthesizing the synergies between SDGs and the preferred adaptation options found in the (I)NDCs, Figure 5 provides some guidance in terms of priorities for implementing the SDGs through adaptation projects. It also highlights which adaptation options are particularly attractive because of the multiple benefits widespread across SDGs. The first five options have pervasive implications for sustainable development, and indeed are mentioned in most countries, as highlighted by the width of the bar. Yet, only a few countries mention options such as water distribution, irrigation efficiency, and heating and cooling, which indeed show a thin bar, even though they support several SDGs (1, 3, 4, 8, 11).

4. Discussion and Conclusions

The (I)NDCs submitted under the Paris Agreement provide a unique wealth of information regarding adaptation priorities across a large number of countries. In this paper, we analyze in detail these documents to define energy use for adaptation. We categorize the adaptation interventions that most strongly influence energy demand and discuss the implications for sustainable development. Both topics have received low recognition in the literature. The climate actions described in the (I)NDCs reveal that several adaptation options consistently mentioned across different countries are associated with energy use either because they are energy-intensive or relate to energy-intensive sectors, because they represent a precondition for access to basic energy services, because they require access to energy in order to spread their benefits and reach targeted population, or because they have the potential to save energy.

Our analysis identifies 20 energy for adaptation options, 6 of them (accounting for 43% of the total observed measures across all countries) with the potential to be energy savings, while the other 14 options are more likely to increase energy use. The majority of countries (65%) plan to rely on renewable sources when mentioning energy-intensive options such as irrigation, desalination, water distribution, space heating, and cooling. Still, the risk of maladaptation remains [48]. Although renewable-based options would not contribute to increase GHG emissions, other dimensions of maladaptation related to distributional implications, high opportunity costs, and path dependency still apply to some of the options identified. Forms of reactive adaptation such as the installation of air conditioning, often in response to urgency, has lower costs in the short-run compared to proactive strategies such as upgrading new and existing buildings, which require higher investments in the short-run, but have larger pay-offs in the long-term, especially in the context of achieving multiple sustainable goals. Demand-side management (DSM), including building management systems, can play an important role in both reducing consumption from cooling and other electricity end uses during peak loads, as well as supporting the integration of renewables-based generation. Failure to integrate heating and cooling needs into the planning process brings a high risk of lock-in in sub-optimal energy-intensive infrastructure [36].

Our analysis points at the continuum between adaptation and development. Of the 20 options identified, desalination, irrigation, water recycling, groundwater recharge, cooling in tropical areas, and early warning systems can be more explicitly linked to adaptation, whereas those related to buildings and improving infrastructure (e.g., transport, electrification, multipurpose dams, medical services, building codes, renewables, energy efficiency, information and education) can be better categorized as development strategies. Renewable energy and energy efficiency have being extensively examined in the context of mitigation and sustainable development, but our analysis shows there is evidence regarding their potential contribution at reducing climate risk as well.

Bearing in mind the subtle difference between adaptation and development, energy use for adaptation as defined in this paper has a strong potential to support development, especially regarding the dimensions articulated by SDG11 (sustainable cities and communities), SDG2 (zero hunger), and SDG3 (good health and well-being). What are the possible leverages that could promote the undocumented energy for adaptation options having widespread development co-benefits (such as renewable-based water distribution) requires further research on policy adoption and implementation.

From a policy viewpoint, the framework proposed highlights adaptation actions with potential co-benefits for mitigation and sustainable development, offering guidance for the (I)NDCs' assessment as well as for designing the mechanisms aimed at promoting mitigation and adaptation while supporting sustainable development in the context of the Paris Agreement. The evidence relating energy use for adaptation and SDGs highlights particularly attractive options that, by supporting several SDGs, could receive priority. Our analysis only elucidates the potential direction adaptation could take, should countries actually implement the options described, within the bounds of uncertainty that varies across countries. Future research is warranted to understand policy adoption decisions and how those vary across climatic conditions, institutional, and socio-economic settings.

Our analysis is intended to set-up a background for future quantitative or qualitative research aimed at (i) evaluating the energy requirements of adaptation and (ii) exploring to what extent adaptation measures can contribute to development while bringing about mitigation co-benefits. Quantifying the energy requirements of the adaptation options identified in this article, accounting for the great heterogeneity across space and technology [20], would provide valuable input for climate policy scenario analysis. Since no single model encompassing all identified options exists, suitable approaches to substantiate the conclusions of this paper with empirical estimates include either a qualitative systematic review of quantitative studies or a quantitative analysis based on a multi-model inter-comparison exercise. Model-based analyses integrating energy for adaptation options and mitigation [3,63–65] are needed to substantiate how the global macroeconomic and environmental implications of adaptation could interact with mitigation in the transition towards sustainability. Such research would complement and enrich the expanding literature on climate policy and SDGs with system perspective that, as of now, has been focusing on mitigation [66,67].

Overall, the analysis presented here confirms the existence of potential trade-offs between adaptation and emission reduction objectives, channeled through negative feedbacks on the energy system. The size of the challenge will depend on the actual choices of national governments. Mitigation remains a priority to reduce the need for adaptation and decarbonize energy sources. At the same time, a careful planning of country-specific and local adaptation measures can play a key role in the transformative change toward a sustainable development.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/15/4085/s1, Table S1: (I)NDCs, Table S2: SDGs.

Author Contributions: Conceptualization, E.D.C. and M.D.; Methodology, E.D.C. and M.D.; Formal analysis, E.D.C., M.D., and A.B.; Investigation, M.D., E.D.C.; Writing—original draft preparation, E.D.C. and M.D.; Writing—review and editing, M.D., A.B. and E.D.C.

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Appendix A

Table A1 summarizes the linkages between energy for adaptation options from the (I)NDCs and the SDGs, along with the supporting literature that substantiates the connections. The database quantifying the number of options contributing to each goal that has been used to generate Figure 5 in the main paper is available online (Supplementary Material.xls), along with the database counting the occurrence of the energy use for adaptation options in the (I)NDCs by country.

Table A1. Linkages between energy use for adaptation in the (I)NDCs and SDGs, and supporting literature

	Goals and Targets (from the 2030 Agenda for Sustainable Development)	Energy for Adaptation Options Identified in the Nationally Determined Contributions	Linkages Explained
SDG 1.	End poverty in all its forms everywhere		
	1.4 By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance	Rural electrification (RE), (Ren-based) Heating/cooling, (Ren-based) Water heating, (Ren-based) Water distribution (RWD), Water harvesting	Access to basic services is fundamental to human development. Rural electricity is recognized to be a key enabling factor for poverty reduction [28]. Modern heating/cooling equipment, minimum and accessible water supply are among the basic comfort elements that ensure decent living standards [25]. Rural electrification can have positive socio-economic impacts [68].
	1.5 By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters	Medical services, Early warning systems (EWS), Building standards (BS), Energy efficiency (EE), Renewable energy (RES)	Development of EWS is a key adaptation response to prevent human and economic losses in case of extreme events. Improved public medical services as well as housing and living conditions help reduce the vulnerability and exposure of the poor to climate-related shocks and disasters [69]. Energy efficiency measures reduce energy expenditure and thus contribute to reducing exposure and alleviating poverty [70]. Efficient use of resources, renewable energy and access to modern energy can free up resources (both finance and time) that can otherwise be used in other productive activities (e.g., educational and employment opportunities) [28,60].
SDG 2.	End hunger, achieve food security and improved nutrition and promote sustainable agriculture		
	2.1 By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round	Food storage (FS), Rural electrification, Renewable energy, Energy efficiency	Food storage and primary processing infrastructure can help reducing post-harvest losses, for example through improved electric-powered preservation (e.g., drying and smoking) and chilling/freezing. Overall, access to more efficient, cleaner, and more affordable energy options is an effective tool for combating extreme hunger by increasing food productivity and reducing post-harvest losses [60,61]. Along with food security, food storage contributes to increase safe and nutritious food access by all people [60,71].
	2.3 By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment	Desalination, Irrigation, Water recycling and reuse, Multipurpose dams, Livestock	Improved irrigation and modern irrigation technologies help increase agricultural productivity [72] and therefore enhance food security [60]. The use of safely treated wastewater has become a means of increasing water availability for irrigation [73]. Practices to keep an adequate thermal comfort for livestock reduce the losses in meat and milk production due to animals' vulnerability to increased heat stress and acclimation [61].

Table A1. *Cont.*

	Goals and Targets (from the 2030 Agenda for Sustainable Development)	Energy for Adaptation Options Identified in the Nationally Determined Contributions	Linkages Explained
	2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality	(Ren-based) Desalination, (Ren-based) Irrigation, Water conservation, Water harvesting, Irrigation efficiency	Clean energy technologies (e.g., wind and solar pumps) and water saving practices can improve the irrigation benefits and therefore contribute to increasing sustainable food production [60]. Water efficient practices (e.g., supplemental irrigation, water harvesting, or shallow groundwater resources) are important for increasing water productivity in rainfed agriculture and reduce the carbon footprint of the agricultural sector [61].
SDG 3.	Ensure healthy lives and promote well-being for all at all ages		
	3.2 By 2030, end preventable deaths of newborns and children under 5 years of age, with all countries aiming to reduce neonatal mortality to at least as low as 12 per 1000 live births and under-5 mortality to at least as low as 25 per 1000 live births	Food storage (FS), Livestock	Undernutrition contributes to the severity of a range of diseases, and is responsible for nearly half of total under-five deaths [74]. By supporting food security and reducing undernutrition [60], food storage techniques contribute to preventing children mortality.
	3.3 By 2030, end the epidemics of AIDS, tuberculosis, malaria and neglected tropical diseases and combat hepatitis, water-borne diseases and other communicable diseases	(Ren-based) Heating/Cooling, Medical services, Building standards (BS), Information and education	Adaptive measures to reduce health risk and diffusion of vector borne disease due to climate change include the implementation and enforcement of health care interventions (e.g., vaccination programs) and educational campaigns as well as the improved quality of residential conditions and health infrastructure (e.g., building insulation, cooling of health care facilities) [7,43].
	3.4 By 2030, reduce by one third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being	Building standards, Food storage	Emergency preparedness is considered an essential feature of modern buildings. When one's sense of security is threatened, their bodies elicit a cascade of biological fight-or-flight responses that alter their physical and psychological functioning [62].
	3.6 By 2020, halve the number of global deaths and injuries from road traffic accidents	Transport (TS)	Experiences in Europe, Latin America, and India show that well-planned and designed sustainable transport measures can play a significant role in improving road safety, as a benefit from restricted private car traffic and the promotion of more energy-efficient modes, such as public transport, cycling, and walking [75].

Table A1. *Cont.*

	Goals and Targets (from the 2030 Agenda for Sustainable Development)	Energy for Adaptation Options Identified in the Nationally Determined Contributions	Linkages Explained
	3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	Rural electrification, Energy efficiency, Renewable energy, Building standards	Switching from traditional cooking methods and fuels to modern, cleaner and more efficient stoves or electricity reduce air pollution [71] and associated mortality and illnesses [43]. Buildings characteristics affect health through several channels (water quality, indoor pollution, thermal comfort) [76].
		Water recycling and reuse, (Ren-based) Water distribution, Renewable energy	Appropriate wastewater collection and treatment helps protect the water quality while significantly reducing the number of people exposed to water-related diseases [73]. Expanding or improving water supply and distribution, including water pumping through renewable energy, helps ensure access to safe water [60]. Water quality in buildings as well as disinfection systems affect health [62]. Overall, modern forms of energy are proved to play an important role in improving access to safe water and sanitation [60].
	3.d Strengthen the capacity of all countries, in particular developing countries, for early warning, risk reduction and management of national and global health risks	Early warning systems	EWSs integrate adaptation with sustainable development and the Sendai Framework for Disaster Risk Reduction [46].
SDG 4.	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all		
	4.1 By 2030, ensure that all girls and boys complete free, equitable and quality primary and secondary education leading to relevant and effective learning outcomes	Rural electrification, Renewable energy	Access to modern forms of energy improves the quality and availability of educational services and increases the likelihood that children will attend and complete schooling (e.g., reducing the time that women and girls spend carrying fuel). In addition, rural electrification helps retain good teachers in rural areas, thus contributing to enhancing the quality of rural education [60].
	4.5 By 2030, eliminate gender disparities in education and ensure equal access to all levels of education and vocational training for the vulnerable, including persons with disabilities, indigenous peoples and children in vulnerable situations	Transport, (Ren-based) Water distribution	As women are more dependent on public transport than men, sustainable and accessible transport planning plays a crucial role in broadening women's access to health and education services, employment, improving the exchange of information, and promoting social cohesion [77]. Women spend far more time than men fetching water that, in the presence of renewable water distribution systems, can otherwise be spent in pursuit of education [60].

Table A1. *Cont.*

	Goals and Targets (from the 2030 Agenda for Sustainable Development)	Energy for Adaptation Options Identified in the Nationally Determined Contributions	Linkages Explained
	4.7 By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development	Information and education (I&E)	Explicitly mentioned in the SD goal and target [78].
	4.a Build and upgrade education facilities that are child, disability and gender sensitive and provide safe, non-violent, inclusive and effective learning environments for all	Rural electrification + (Ren-based) Heating/cooling, (Ren-based) Water heating, (Ren-based) Water distribution + Building codes	Access to electricity and drinking water are explicitly mentioned in the SD target [78]. Access to air conditioning positively affects children cognitive functions during heatwaves [76].
SDG 5.	Achieve gender equality and empower all women and girls		
	5.2 Eliminate all forms of violence against all women and girls in the public and private spheres, including trafficking and sexual and other types of exploitation	Rural electrification	Rural electrification can play an important role in eliminating violence against women, as it leads to lower acceptance of intimate partner violence (IPV). It is especially access and higher exposure to information via TV sets that causes the difference in IPV acceptance [79].
		(Ren-based) Water distribution, Water harvesting, Water conservation	Women and young girls often go out to collect fuel, fodder, and water for homes and, particularly in conflict or post conflict situations, this can present a threat to their security [80].
	5.4 Recognize and value unpaid care and domestic work through the provision of public services, infrastructure and social protection policies and the promotion of shared responsibility within the household and the family as nationally appropriate	(Ren-based) Water distribution, Renewable energy, Transport	The lack of access to improved water supply places a disproportionate burden on women and girls who tend to be the primary collectors of water for the family [81]. Access to efficient cook stoves and modern forms of energy help alleviating the burden placed on women and children in fuel collection [60]. The burden of women's housework reduces as a result of improved public transport access [82].
	5.5 Ensure women's full and effective participation and equal opportunities for leadership at all levels of decision-making in political, economic and public life	Transport standards, Rural electrification	Poor access to transport limits women's capacity to extend their economic enterprises, thereby reducing household income and overall national productivity [83]. Access to modern energy services has the potential to empower women by improving their income-earning, entrepreneurial opportunities, autonomy, and reducing drudgery [28]. Rural electrification increases female employment [68].

Table A1. *Cont.*

	Goals and Targets (from the 2030 Agenda for Sustainable Development)	Energy for Adaptation Options Identified in the Nationally Determined Contributions	Linkages Explained
	5.6 Ensure universal access to sexual and reproductive health and reproductive rights as agreed in accordance with the Programme of Action of the International Conference on Population and Development and the Beijing Platform for Action and the outcome documents of their review conferences	Rural electrification, Medical services	Women's reproductive health is seen as benefiting from electrification, as women with access to TV, are more informed on many health messages, including reproductive health and contraceptive methods, prevention of sexually transmitted diseases, and health checks for breast cancer and colon cancer [84].
	5.b Enhance the use of enabling technology, in particular information and communications technology, to promote the empowerment of women	Rural electrification	Rural electrification facilitates access to technology. Electrification helps foster "connective" applications such as radio, television, information, cell phone [85].
SDG 6.	Ensure availability and sustainable management of water and sanitation for all		
	6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all	(Ren-based) Desalination, (Ren-based) Water distribution	Desalination contributes to alleviating fresh water scarcity problems and increasing the supply of drinking water [44]. Expanding or improving water supply and distribution, including water pumping through renewable energy helps ensuring access to safe water [60].
	6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations	Rural electrification, Renewable energy	Modern forms of energy are proved to play an important role in improving access to safe water and sanitation (solar water disinfection) [60].
	6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	Water recycling and reuse	Explicitly mentioned in the SD goal and/or target. Appropriate wastewater collection and treatment helps protect the water quality while significantly reducing the number of people exposed to water-related diseases [73].
	6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	Water conservation, Irrigation efficiency, Information and Education	Water efficiency and demand management practices include a variety of measures that include improving use efficiency through improved technologies (e.g., increased efficiency in irrigated agriculture, water metering) but also awareness raising and education campaigns [44].
		Multipurpose dams, Water harvesting	Rainwater harvesting and groundwater recharge as well as multipurpose dams help address water scarcity through water augmentation and storage [44].
SDG 7.	Ensure access to affordable, reliable, sustainable and modern energy for all		
	7.1 By 2030, ensure universal access to affordable, reliable and modern energy services	Rural electrification	Explicitly mentioned in the SD goal and target [78].

Table A1. *Cont.*

	Goals and Targets (from the 2030 Agenda for Sustainable Development)	Energy for Adaptation Options Identified in the Nationally Determined Contributions	Linkages Explained
	7.2 By 2030, increase substantially the share of renewable energy in the global energy mix	(Ren-based) Desalination, (Ren-based) Irrigation, (Ren-based) Water distribution, (Ren-based) Heating/cooling, (Ren-based) Water heating, Renewable energy	Explicitly mentioned in the SD goal and target [78].
	7.3 By 2030, double the global rate of improvement in energy efficiency	Energy efficiency, Building standards, Transport systems/standards	Explicitly mentioned in the SD goal and target [78].
SDG 8.	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all		
	8.2 Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labor-intensive sectors	Irrigation, (Ren-based) Irrigation, Renewable energy, Multi-purpose dams	Irrigation stimulates agricultural productivity and economic growth. Dam-based irrigation can have negative effects where dams are placed, but they can have positive impacts on poverty and wages in downstream villages [72].
	8.3 Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through access to financial services	Rural electrification, Information and education	Cleaner energy options can enhance working conditions and open opportunities to generate livelihoods, increase the number of jobs, and provide decent work. Access to affordable energy options from gaseous and liquid fuels and electricity can assist enterprise development [60]. The digital revolution facilitates access to information and can have positive impacts on economic growth, but it needs to come along with good institutions and human capital [86].
	8.4 Improve progressively, through 2030, global resource efficiency in consumption and production and endeavor to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programmes on Sustainable Consumption and Production, with developed countries taking the lead	Rural electrification, Energy efficiency, Water conservation, Building standards	Energy efficiency and water conservation have the potential to improve global resource efficiency. Building rating systems (RSs) have initially been developed to promote the reduction of energy and water use and waste [62].
	8.8 Protect labor rights and promote safe and secure working environments for all workers, including migrant workers, in particular women migrants, and those in precarious employment	(Ren-based) Heating/Cooling	Investments in heating and cooling equipment represent an option for firms to adapt to the negative impact that temperature shocks may have on workers [15].
SDG 9.	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation		

Table A1. *Cont.*

	Goals and Targets (from the 2030 Agenda for Sustainable Development)	Energy for Adaptation Options Identified in the Nationally Determined Contributions	Linkages Explained
	9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all	Rural electrification, (Ren-based) Desalination, Multipurpose dams, Irrigation, (Ren-based) Irrigation, Irrigation Efficiency, Transport	According to the UN's definition, infrastructure includes transport, irrigation, energy and information, and communication technology [78]. Here are considered options that support this infrastructure resilience and deployment.
		Transport	Explicitly mentioned in the SD goal and target [78].
	9.2 Promote inclusive and sustainable industrialization and, by 2030, significantly raise industry's share of employment and gross domestic product, in line with national circumstances, and double its share in least developed countries	Rural electrification, Renewable energy, Energy efficiency	Rural electrification contributes to industrial development and GDP increase [68,87]. Diversification of energy sources and energy efficiency can help reduce energy costs [31].
	9.3 Increase the access of small-scale industrial and other enterprises, in particular in developing countries, to financial services, including affordable credit, and their integration into value chains and markets	Rural electrification, Renewable energy	
	9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities	Building standards + Energy efficiency, Rural electrification	Mentioned in the SD goal and target [78].
	9.c Significantly increase access to information and communications technology and strive to provide universal and affordable access to the Internet in least developed countries by 2020	Rural electrification	Solar electrification helps foster connective applications such as radio, television, information, cell phone [85].
SDG 10.	Reduce inequality within and among countries		
	10.1 By 2030, progressively achieve and sustain income growth of the bottom 40 percent of the population at a rate higher than the national average	Energy efficiency, Renewable energy, Rural electrification, (Ren-based) Water distribution, Water conservation, Water harvesting	Efficient use of resources, renewable energy, and access to modern energy can free up resources (both finance and time) that can be used for other productive activities (e.g., educational and employment opportunities) [28,60].
	10.2 By 2030, empower and promote the social, economic and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or other status	Renewable energy	Decentralized renewable energy systems (e.g., home- or village-scale solar power) can enable a more participatory, democratic process for managing energy-related decisions within communities [28].

Table A1. *Cont.*

	Goals and Targets (from the 2030 Agenda for Sustainable Development)	Energy for Adaptation Options Identified in the Nationally Determined Contributions	Linkages Explained
	10.3 Ensure equal opportunity and reduce inequalities of outcome, including by eliminating discriminatory laws, policies and practices and promoting appropriate legislation, policies and action in this regard	Renewable energy, Transport	Sustainable public transport options play a crucial role in broadening access to basic services and job opportunities as well as promoting social cohesion [77]. Decentralized renewable energy systems (e.g., home- or village-scale solar power) can enable a more participatory, democratic process for managing energy-related decisions within communities [28].
SDG 11.	Make cities and human settlements inclusive, safe, resilient and sustainable		
	11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums	(Ren-based) Heating/cooling, (Ren-Based) Water heating, Rural electrification, Building standards, (Ren-based) Water distribution	Safe and basic housing services imply access to modern forms of energy, durable and resilient homes which, at the community level, require infrastructure such as electricity and water distribution [62]. Modern heating/cooling equipment, minimum and accessible water supply are among the basic comfort elements that ensure decent living standards [25].
	11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons	Transport	Explicitly mentioned in the SD goal and target. Urban centers rely on transport for their daily functioning. A resilient public transportation system is essential to ensure access to goods and services, as well as employment, production, and livelihoods opportunities, and is critical for effective disaster response [51].
	11.3 By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries	Building standards	
	11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations	Medical services	Direct economic costs include non-market impacts on health-morbidity and mortality. Improved hospital and infrastructure for medical services, as well as a more extended network of health centers contribute to resilience, by allowing a quicker and more effective making response in case of emergency [36].
		Multipurpose dams	Multipurpose dams can contribute to flood control, reducing water-related disasters [45].
	11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	Transport systems + water recycling and reuse, Energy efficiency, Renewable energy + rural electrification	The climate imperatives to deploy more efficient technologies and to reduce reliance on energy from fuel combustion—including electrification of end-uses—have co-benefits in terms of reduced pollution. Policies that stimulate energy efficiency reduce local air pollutants [88,89]. Regulatory regimes, in particular vehicle standards regimes, contribute to reduce the health impact of road transport pollution [90].

Table A1. *Cont.*

	Goals and Targets (from the 2030 Agenda for Sustainable Development)	Energy for Adaptation Options Identified in the Nationally Determined Contributions	Linkages Explained
	11.b By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015–2030, holistic disaster risk management at all levels	Early warning systems, Information and education	EWS, I&E are key strategies to address disaster risk, and belong to those strategies that contribute to the Sendai Framework. Examples of knowledge sharing activities and implementation of early warning system, and how they contribute to risk reduction, are described in [46].
SDG 12.	Ensure sustainable consumption and production patterns		
	12.2 By 2030, achieve the sustainable management and efficient use of natural resources	Water conservation, Water harvesting, Energy efficiency, Renewable energy	Renewable and energy efficiency can reduce pressure on natural resources, as access to modern forms of energy means less disturbance for local biodiversity and lower reliance on wood and other natural resources (e.g., forest). Recycling activities—including wastewater treatment and reuse—contribute to reducing pressure on natural resources such as fresh water [28].
	12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses	Food storage	During the crop transition from farm to consumer, crops undergo several operations-harvesting, threshing, cleaning, drying, storage, processing, and transportation. Storage plays a vital role in the food supply chain, and several studies reported that maximum losses happen during this operation. [54,55,91].
	12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment	Water recycling and reuse	Appropriate wastewater collection and treatment helps protect the water quality while significantly reducing the number of people exposed to water-related diseases [73].
	12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature	Information and education	Explicitly mentioned in the SD target [78].
SDG 14.	Conserve and sustainably use the oceans, seas and marine resources for sustainable development		
	14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution	Water conservation, Water recycling and reuse, Water harvesting, Irrigation efficiency Information and education	Measures that restrict overuse and pollution of water at its source, or improve water treatment capacity, contribute to the reduction of water bodies' pollution. Improving farmer knowledge on sustainable agricultural practices helps avoid nutrient excess dosages, and therefore leakage [44]. Overall, awareness-raising campaigns are an effective way of reducing marine debris [92]

Table A1. *Cont.*

	Goals and Targets (from the 2030 Agenda for Sustainable Development)	Energy for Adaptation Options Identified in the Nationally Determined Contributions	Linkages Explained
	14.2 By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans	Water conservation	
	14.3 Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels	Renewable energy, Energy efficiency	Emission reduction induced by the deployment of renewable energy and energy efficiency practices reduces global emissions and slows down ocean acidification rates [28,71].
SDG 15.	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss		
	15.1 By 2020, ensure the conservation, restoration, and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements	Rural electrification, Energy efficiency	Access to modern energy services and energy efficiency reduce the need to rely on firewood taken from forests and hence contribute to halting deforestation [28,60,71].
	15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world	Water harvesting including groundwater recharge, Water conservation & improved water use efficiency (including water metering), Irrigation efficiency	Water harvesting, water conservation, and improved efficiency are all options that contribute to reduce water needs. Measures aimed at improving water use efficiency can also lead to benefits in terms of improved soil moisture retention capacity [45]. Irrigation efficiency can also be improved through altering farming practices and conservation tillage that help improve soil moisture conservation [44].
SDG 16.	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels		
	16.1 Significantly reduce all forms of violence and related death rates everywhere	Water conservation, Water harvesting, Multi-purpose dams, Irrigation, (Ren-based) Irrigation, Irrigation efficiency	Water availability, and therefore all options that increase water supply, as well as agriculture dependency (agriculture output as a share of GDP) increase the likelihood of occurrence of hydro-political interactions defined as either conflicts or cooperation [93].

Table A1. *Cont.*

	Goals and Targets (from the 2030 Agenda for Sustainable Development)	Energy for Adaptation Options Identified in the Nationally Determined Contributions	Linkages Explained
	16.5 Substantially reduce corruption and bribery in all their forms	Renewable energy, Energy efficiency	Renewable energy, by reducing reliance on oil and oil rent, can contribute to reducing the corruption associated with oil-rent-seeking activities. The empirical evidence suggests that non-oil natural resources, which management is more apparent to the public, are less prone to corruption [94].
SDG 17.	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development Finance		
	17.7 Promote the development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries on favorable terms, including on concessional and preferential terms, as mutually agreed	Renewable energy, Energy efficiency	Evidence from CDM projects shows the significant potential of technology transfer associated with renewable energy sources such as solar and wind power and measures to improve energy efficiency at the household level or in services [95].
	17.8 Fully operationalize the technology bank and science, technology and innovation capacity-building mechanism for least developed countries by 2017 and enhance the use of enabling technology, in particular information and communications technology	Rural electrification	10% of world electricity consumption is dedicated to ICTs and one cannot access the internet without electricity. Expanding access to energy and to the Internet can be done concurrently. Studies show that solar electrification plays an important role in fostering "connective" applications such as radio, television, information, cell phone [85].

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