Food and Agriculture Organization of the United Nations

THE SMALL-SCALE FISHERIES AND ENERGY NEXUS

Opportunities for renewable energy interventions

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by

Manas Puri

Ana Kojakovic

Luis Rincon

Jhuliana Gallego

Ioannis Vaskalis

and

Irini Maltsoglou

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PREPARATION OF THIS DOCUMENT

This report was developed for the Value Chain Development Team of the Fisheries and Aquaculture Division, under the guidance of Nianjun Shen and Ansen Ward and in collaboration with the Office of Climate Change, Biodiversity and Environment.

The authors of this report are Manas Puri, Ana Kojakovic, Luis Rincon, Jhuliana Gallego, Ioannis Vaskalis and Irini Maltsoglou from the Office of Climate Change, Biodiversity and Environment.

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Access to reliable, affordable energy is important for the utilization of fish and the development of associated livelihoods. Small-scale fishery value chain operators are seldom seen as heavy energy consumers. However, energy is vital for many post-harvest activities related to processing, preservation (especially the cold chain) and value addition.

Renewable sources of energy are gaining traction worldwide. Solar, wind power, biomass energy and geothermal heat energy are already used in applications in food value chains. Renewable energy can provide energy solutions in situations where there are challenges with traditional energy supplies.

Renewable energy also has the capacity to reduce the carbon footprint of food value chains and help mitigate against climate change. Yet, the link between renewable energy and small-scale fisheries and aquaculture is not well documented.

This publication introduces the current situation and proposes a way forward with regard to the use of renewable energy in small-scale fisheries. It provides general guidance for decision-makers and development specialists on the choices, benefits and challenges related to renewable energy use and uptake in small-scale fisheries. The publication will contribute to the implementation of the FAO Code of Conduct for Responsible Fisheries (CCRF) and the FAO Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Alleviation (SSF Guidelines). FAO's objectives relate to better production, better nutrition and better environment.

CONTENTS

Preparation of this document iii
Acknowledgements xiii
Abbreviations and acronyms xv
Executive summary xvii

1. INTRODUCTION 1
1.1 The fisheries and aquaculture sector 2
1.2 Energy use in fisheries and aquaculture 4
1.3 Key issues on energy use 5
1.3.1 Modernizing fisheries in developing countries will increase energy demand 6
1.3.2 Lack of energy and cooling leads to higher losses 7

2. STRUCTURE OF AND ENERGY USE ALONG THE VALUE CHAIN 9
2.1 Energy use at each stage of the value chain 9
2.1.1 Production stage 10
2.1.2 Handling and storage 12
2.1.3 Processing 15
2.1.4 Distribution and marketing 16

3. DESCRIPTION OF THE RENEWABLE ENERGY TYPES 17
3.1 Introduction to energy forms 17
3.1.1 Electricity 17
3.1.2 Thermal energy: heat 18
3.1.3 Energy supply and demand 18
3.2 Renewable energy sources 18
3.2.1 Energy storage and renewables 19
3.2.2 Sustainable siting for renewable energy sources 20
3.3 Description of renewable energy sources 21
3.3.1 Solar energy 21
3.3.2 Wind energy 26
3.3.3 Bioenergy 30
3.3.4 Hydroelectric energy 37
3.3.5 Geothermal energy 41
3.3.6 Marine energy 46

4. SPECIFIC RENEWABLE ENERGY INTERVENTIONS BY VALUE CHAIN STAGES 49
4.1 How can renewable energies intervene in a fish value chain? 49
4.1.1 Interventions already applied to fish value chains 51
4.1.2 Interventions currently applied in a different value chain but also suitable for fisheries 52
4.1.3 Interventions that can theoretically be appliedto fisheries 52
4.2 Opportunities for renewable energy interventions in small-scale fish value chains 53
4.2.1 Capture 53
4.2.2 Aquaculture 54
4.2.3 Aggregation and storage 55
4.2.4 Processing 57
4.2.5 Marketing and distribution 59

5. TECHNOLOGY SPECIFICATIONS AND COSTS 61
5.1 Cost of renewable energy sources technologies 61
5.2 Technology specifications 63
5.3 Example 1: solar freezers in rural fish farmer communities 64
5.3.1 Case study: the cool women of Malaita 65
5.3.2 Renewable energy intervention: solar photovoltaic system 66
5.4 Example 2: solar fishing lights in lake victoria 68
5.4.1 Case study: the lumina project – Lake Victoria, East Africa 68
5.4.2 Renewable energy intervention: solar photovoltaic system 69

6. OPPORTUNITIES AND CHALLENGES FOR RENEWABLE ENERGY INTERVENTIONS 73
6.1 Key issues for market development 73
6.1.1 Cost and financing of renewable energy equipment 73
6.1.2 Policy environment and local capacity 74
6.1.3 Awareness and acceptance of technology 74
6.2 Recommendations 75

7. REFERENCES 77

8. APPENDIX: TECHNOLOGY SPECIFICATIONS, INVESTMENT AND RUNNING COSTS 89

BOXES

1. Solar energy case study: Barbados 25
2. Wind energy case study: Cabo Verde 29
3. Bioenergy case study: Egypt 35
4. Hydroelectric energy case study: Mozambique 40
5. Geothermal energy case study: Indonesia 45

FIGURES

1. Global production of capture fisheries and aquaculture (2008–2019) 2
2. Top ten fish producers (capture fisheries and aquaculture) 3
3. Fish production by regions 3
4. Share of fish production from capture fisheries and aquaculture across the regions 4
5. A simple depiction of a small-scale fish value chain 5
6. Employment in fisheries by regions 6
7. The structure of the various processes in a typical small-scale value chain 9
8. Energy used at each stage of a typical small-scale fish value chain 10
9. Share of motorized and non-motorized vessels across regions 10
10. End use of global fish production by developing and developed countries in 2018 13
11. Types of energy 17
12. Global installed capacity of renewable energy sources 19
13. Surplus versus shortage of energy with an energy storage system 20
14. Overview of direct and indirect solar heating systems 22
15. Global long-term average of photovoltaic power potential 24
16. Schematic overview of a wind turbine and its operation 26
17. Global wind power density at 100 m 28
18. Bioenergy conversion routes and final uses 31
19. Overview of pelletizing process 32
20. Biomass charcoal briquettes production process 33
21. Impoundment and run-of-river hydropower installations 38
22. Global hydropower potential 39
23. Overview of the three different types of geothermal power plants 42
24. Overview of geothermal heat utilization 43
25. Global potential for direct use of geothermal energy for heating purposes 44
26. Directions in renewable energy interventions 50
27. Types of renewable energy interventions for fisheries 51

28. Improved small-scale value chain 53
29. Opportunities for renewable energy interventions in improved small-scale capture fisheries 54
30. Opportunities for renewable energy interventions in the improved small-scale value chain for aquaculture 55
31. Opportunities for renewable energy interventions at the improved small-scale for aggregation and storage 56
32. Opportunities for renewable energy interventions in improved small-scale processing 58
33. Opportunities for renewable energy interventions in improved small-scale marketing and distribution 59
34. Example of a solar cooler/freezer 65
A.1 Example of a solar freezer 90
A.2 Off-grid and on-grid operation for solar freezers 92
A.3 Example of a fishing lamp 96
A.4 Example of a solar powered fishing boat 99
A.5 Example of an automatic aerator 101
A.6 Example of fish feeding 104
A.7 Example of a solar water pump 106
A.8 Example of an ice maker machine 109
A.9 Example of a solar portable cooler/freezer 113
A.10 Example of a solar cold storeroom 115
A.11 Example of a fish smoker 118
A.12 Example of an electric dryer 121
A.13 Example of a solar dryer 123
A.14 Example of fish fillets 125
A.15 Example of a skinned fish 128
A.16 Example of fish scaling 130
A.17 Example of a vacuum sealer machine 133
A.18 Example of a can sealing machine 135
A.19 Example of canned fish 136
A.20 Example of a solar vending cart with chest cooler/freezer 138
A.21 Example of a biogas motor engine 141

TABLES

1.	Size of vessels and energy consumption	11
2.	Energy used in aquaculture production by type of aquaculture system	11
3.	Energy demand to produce ice in temperate and tropical regions	14
4.	Energy use for cold storage and transport in the United Kingdom of Great Britain and Northern Ireland	15
5.	PV installed capacity per region in 2020	24
6.	Effect of wind turbine installed capacity on hub height and rotor diameter	27
7.	Wind energy installed capacity per region in 2020	29
8.	Bioenergy production per region in 2018 and 2020	34
9.	Hydropower installed capacity per region in 2020	40
10.	Geothermal direct use installed capacity per region in 2019	45
11.	Marine energy installed capacity per region in 2020	47
12.	Typical installed and operating and maintenance costs for renewable energy sources	61
13.	Technology specifications and cost for chest freezer	65
14.	Technical specifications, investment and running cost for solar freezer PV systems	66
15.	Investment and running cost for solar chest freezer	67
16.	Technology specifications and cost for fishing lights	69
17.	Technical specifications, investment and running cost for solar lamp/fishing lights photovoltaic systems	70
18.	Investment and running cost for fishing lights PV system	71
A.1	Technology specifications and cost for solar freezer	89
A.2	Technical specifications, investment and running cost for solar portable freezer photovoltaic systems	90
A.3	Investment and running cost for solar chest freezer photovoltaic systems	93
A.4	List of equipment included in appendix, and remarks	94
A.5	Technology specifications and cost for solar lamps/fishing lights	96
A.6	Technical specifications, investment and running cost for solar lamp/fishing lights photovoltaic systems	97
A.7	Investment and running cost for solar lamps/fishing lights photovoltaic systems	98
A.8	Technology specifications and cost for electric boat motor engine	98
A.9	Technical specifications, investment and running cost for electric boat motor engine photovoltaic system	99
A.10	Investment and running cost for electric boat motor engine photovoltaic systems	100
A.11	Technology specifications and cost for solar aerator	101
A.12	Technical specifications, investment and running cost for solar aerator photovoltaic systems	102
A.13	Investment and running cost for solar aerator photovoltaic systems	103
A.14	Technology specifications and cost for solar automatic fish pond feeder	103

A.15 Technical specifications, investment and running cost for solar automatic fish pond feeder photovoltaic systems 104
A.16 Investment and running cost for solar automatic fish pond feeder photovoltaic systems 105
A.17 Technology specifications and cost for solar water pump 106
A.18 Technical specifications, investment and running cost for solar water pump photovoltaic system 107
A.19 Investment and running cost for solar water pump photovoltaic system 108
A.20 Technology specifications and cost for ice making machines 108
A.21 Technical specifications, investment and running cost for ice making machines photvoltaic system 109
A.22 Investment and running cost for flake ice making machines photovoltaic system 110
A.23 Investment and running cost for cube ice making machines photovoltaic system 111
A.24 Investment and running cost for block ice making machines photovoltaic system 111
A.25 Technology specifications and cost for solar portable freezer 112
A.26 Technical specifications, investment and running cost for solar portable freezer photovoltaic system 113
A.27 Investment and running cost for solar portable freezer photovoltaic system 114
A.28 Technology specifications and cost for solar cold storeroom 115
A.29 Technical specifications, investment and running cost for solar cold storeroom photovoltaic system 116
A.30 Investment and running cost for solar cold storeroom photovoltaic system 117
A.31 Technology specifications and cost for fish smoker kilns 117
A.32 Technology specifications and cost for electric fish smoker 118
A.33 Technical specifications, investment and running cost for electric fish smoker photovoltaic system 119
A.34 Investment and running cost for electric smoker photovoltaic system 120
A.35 Technology specifications and cost for electric dryer 120
A.36 Technical specifications, investment and running cost for electric dryer photovoltaic system 121
A.37 Investment and running cost for electric dryer photovoltaic system 122
A.38 Technology specifications and cost for solar dryer 123
A.39 Technical specifications, investment and running cost for solar dryer photovoltaic system 123
A.40 Investment and running cost for solar dryer photovoltaic system 124
A.41 Technology specifications and cost for fish filleting machines 125
A.42 Technical specifications, investment and running cost for fish filleting machines photovoltaic system 126
A.43 Investment and running cost for fish filleting machines photovoltaic system 127
A.44 Technology specifications and cost for fish skinning machines 127
A.45 Technical specifications, investment and running cost for fish skinning machines photovoltaic system 128

A.46 Investment and running cost for fish skinning machines photovoltaic system 129
A.47 Technology specifications and cost for fish scaling machines 130
A.48 Technical specifications, investment and running cost for fish scaling machines photovoltaic system 130
A.49 Investment and running cost for fish scaling machines photovoltaic system 131
A.50 Technology specifications and cost for vacuum sealer machines 132
A.51 Technical specifications, investment and running cost for vacuum sealing machines photovoltaic systems 133
A.52 Investment and running cost for vacuum sealing machines photovoltaic system 134
A.53 Technology specifications and cost for can sealing machines 135
A.54 Technical specifications, investment and running cost for can sealing machines photovoltaic system 136
A.55 Investment and running cost for can sealing machines PV system 137
A.56 Technology specifications and cost for solar vending cart/bike/motorbike with chest freezer 138
A.57 Technical specifications, investment and running cost for solar vending cart photovoltaic system 139
A.58 Investment and running cost for solar vending cart photovoltaic system 140
A.59 Technology specifications and cost for gas motor engine 140
A.60 Technology specifications and cost for bio-oil motor engine 141

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ABBREVIATIONS AND ACRONYMS

BEFS	Bioenergy and Food Security Approach
CGS	credit guarantee scheme
CHP	combined heat and power
FTT	FAO-Thiaroye Processing Technique
GHG	greenhouse gases
GHI	global horizontal irradiance
LPG	liquified petroleum gas
O&M	operations and maintenance
MPPT	maximum power point tracking
PAHs	polycyclic aromatic hydrocarbons
PV	photovoltaics
SIDS	Small Island Developing States
SVOs	straight vegetable oils
SWH	solar water heating industry
WEC	wave energy converters

EXECUTIVE SUMMARY

Energy and agrifood systems are closely intertwined. Energy is needed at all stages of the agrifood system to produce food, transport it, store it and prepare it for markets, etc. Overall, energy is an intrinsic element for the livelihood of all actors across the value chain. This interconnection becomes even more important when considering climate change and its impacts, and the sustainable development ambitions of the world.

Approximately 30 percent of the world's energy is consumed within agrifood systems (FAO, 2011) and energy use accounts for a third of their greenhouse gas emissions (Crippa *et al.*, 2021). As agrifood systems develop and transform into modern food systems, current and future energy demand will need to be met by stronger and more stable sustainable energy solutions. Renewable energy can play a key role in modernizing food systems through innovation, stable access to energy and access to green energy.

The world has been striving to achieve access to sustainable energy for all by 2030 but there is a lag in progress, especially in the provision of access to electricity, cooking and drying fuels. There are currently 2.6 billion people without access to clean fuels and technologies for cooking, with 61 percent of them in Asia and 36 percent in Africa. The agrifood sector can be a driver for the transition (FAO, 2020).

Fisheries and aquaculture are central sectors and elements of global food systems. Sustainable fisheries and aquaculture play a crucial role in food and nutrition security and provide a source of livelihood for millions of people globally, especially in some of the world's most food-limited regions.

Small-scale fisheries are a central contributor to fishery systems. Large numbers of people are involved in small-scale fisheries, the related supply chain and the services provided by the chain. Small-scale fishing communities can be found everywhere around the world, including in mountain lake areas, island coasts and coastal areas. While no definitive statistics exist, the general understanding is that the sector employs half of the world's 51 million fishers. These populations are mostly located in developing countries and produce close to half of the global fish production and the fish consumed in the developing world.

In addition, in many least developed countries of Africa and Asia, fish accounts for more than 50 percent of the total animal protein intake. In almost all these countries, small-scale fisheries provide over three-quarters of the domestic fish supply. An estimated 59.51 million people were engaged (on a full-time, part-time or occasional basis) in the primary sector of capture fisheries (39.0 million people) and aquaculture (20.5 million people) in 2018. Of all those engaged in primary production, most are in developing countries, and most are small-scale, artisanal fishers and aquaculture workers. The highest numbers of workers are in Asia (85 percent), followed by Africa (9 percent), the Americas (4 percent), and Europe and Oceania (1 percent each). Many more people are involved in part-time or seasonal fisheries activities, and the benefits of fish consumption are much more widely significant around the world. While the fish species involved, vessels and fishing methods, and management approaches vary widely around the world, and within particular regions, many of the resource use, community impact and policy issues are similar (FAO, 2020).

The use of solar energy for cooling and cold storage, for instance, is increasing in rural communities in sub-Saharan Africa and Asia due to the decreasing costs of these technologies. The cost of electricity from solar photovoltaics and wind decreased by 82 percent and 40 percent, respectively between 2010 and 2019. The result has been that in many countries renewable energy is now either on a par with, or the lowest-cost option for new electricity generation (IRENA, 2020).

There is increasing scope and need to promote the use of renewable energy for applications at all stages of the small-scale fisheries and aquaculture value chains. Solar energy in particular can be used to power several processes within the fisheries and aquaculture value chain. This includes operations like powering lights for fishing, aquaculture equipment (feeders, pumps, aerators, security lighting), charging electric motors for fishing, running processing equipment, ice making, chilling and cold storage, including in transport and retail applications. Furthermore, biofuels can be used where transport fuels are required, such as for vending carts and fish distribution on motorbikes. In countries where geothermal resources are present, geothermal heat can be used for warming water in aquaculture systems, and as an energy source for fish drying. Micro-hydroelectric systems can provide clean electricity for aquaculture (FAO, 2021a). However, it is important to note that not all technologies are equally applicable and viable across countries and need to be aligned with country realities and needs.

This report focuses on the role that renewable energy can play in the small-scale fisheries sector by providing an overview of possible renewable energy options, the context and setting of small-scale fisheries value chains, how energy is used along the value chain and where it could play a role in improving livelihood, productivity and access to markets for all stakeholders involved.

Renewable energy sources can be utilized both at small and large scale, to generate electricity or heat, in configurations operating either on- or off-grid. The energy production potential varies across different geographic areas and depends on the resource availability, location of the production system and the characteristics of the energy transformation technology that is used. The report provides important background information on different renewable energy options, focusing on solar and wind energy, hydropower, bioenergy, geothermal and marine energy. For each renewable energy source the main technical factors affecting the system output, area requirements and siting considerations that have to be taken into account are explained. The overall global potential and installed capacity are presented and disaggregated between different regions, and a case study on the status of a particular renewable energy source in a specific country is given. For each renewable energy source applicable, technical solutions in the fisheries value chains are described.

The following sections of the report look at how energy is used across the fisheries value chain. They identify the impact of low energy use across the value chain, and further investigate how renewable energy can modernize the small-scale fisheries value chain. The generic fish value chain is formed by a series of interlinked activities that start from fish production up to fish consumption. While energy is required at all stages of the value chain, the type of energy varies. For instance, oil and diesel are required to power vessels to catch fish, whereas at the storage stage, electricity is needed to power refrigeration equipment. As countries develop, their energy consumption increases, likewise in the fisheries sector. Currently, fossil fuels are the main source of energy in the fisheries value chain. The challenge therefore is to ensure that energy access in the fisheries value chain is increased in a way that minimizes its impact on climate change and is generally sustainable. Renewable energy can therefore offer a solution. The report first looks at the energy use at each step of the value chain, the technologies currently being used and the main challenges relating to energy use in the fisheries value chain. It further delves into identifying specific renewable energy interventions that can be used along the fisheries value chain to increase efficiency and reduce losses.

The specific renewable energy interventions by value chain stages present a range of options suitable for small-scale fisheries value chains. Most of the interventions proposed are based on the country profiles published by the FAO Fisheries Division. The renewable energy interventions considered can be broadly classified into three types: a) interventions already applied to fish value chains, b) interventions currently applied in a different value chain but that are also suitable for fisheries, and c) interventions that can theoretically be applied to fisheries. This report provides examples for each of these interventions. Similarly, the appendix provides examples of the technical specifications and costs associated with renewable energy-based equipment suitable for use in a fish value chain.

The report concludes with possible recommendations and suggestions for a way forward.

1. INTRODUCTION

Agriculture and food systems are both contributors to climate change and are at the same time impacted by it. Globally, around a quarter of global greenhouse gas (GHG) emissions originate in the agriculture sector. At the same time, agriculture has the potential to significantly contribute to mitigating climate change through new practices and technologies that can reduce the carbon footprint of food production.

Global food systems depend on energy to produce, process, transport and cook food. Over the past five decades, global food production has greatly benefited from the availability of inexpensive fossil fuels. As a result, the current global food system has come to rely heavily on fossil fuels. The fisheries and aquaculture sector is no exception: GHG emissions mainly come from the use of fossil fuels, although using non-fuel products in fish production and associated activities may also release GHG (e.g. loss of refrigerants) (He *et al.*, 2018). Energy is needed as fuel to power tractors, water pumps on farms to produce food, and further down the value chain electricity, which is often produced from fossil fuel and needed to process, transport, package and market food.

The global food system currently consumes 30 percent of the world's available energy and is responsible for around 20 percent of the world's GHG emissions (FAO, 2011). Nevertheless, differences are found in the way energy is used in local agrifood chains across countries and regions. In many developing countries, access to modern energy is limited. The inadequate availability of electricity in rural areas, where the majority of the food is produced, translates into a limited availability of storage and processing capacity, all which are essential for producing higher value products. This not only limits the possibility of producing higher value products, but also results in higher food losses due to the lack of modern cold storage and packaging that can increase the shelf life of food. It is estimated that globally around 14 percent of all food is lost between the production and processing stages of the food chain. The limited availability of cold storage and modern processing and packaging technology is one of the reasons for such high losses in many developing countries.

Therefore, in order to support the development of the agrifood chains in developing countries, the energy supply in rural areas needs to increase. We know that modernizing agrifood systems by increasing the use of fossil fuels, as in the past, is no longer a sustainable option. Consequently, the challenge lies in how to provide energy that is economically viable and environmentally sustainable and furthermore, avoids GHG emissions. Nonetheless, it also presents a unique opportunity to develop countries and progressively move towards better and cleaner energy technologies. Moreover, countries can develop a comparative advantage by using renewable energy in the agrifood chain, including the fisheries value chain.

This report aims to show the link between energy use and small-scale fisheries and aquaculture value chains. Informed by this, it seeks to explore specific renewable energy technologies that can improve the efficiency of small-scale fisheries and aquaculture activities, reduce losses and overall enable small-scale fishers, fish farmers and fish workers to improve their incomes.

The report also seeks to support the achievement of the 2030 Agenda for Sustainable Development – specifically Sustainable Development Goal (SDG) 7 (affordable and clean energy), as well as SDG 12 (responsible consumption and production), SDG 13 (climate change); SDG 14 (marine resources) and SDG 9 (infrastructure, industry and innovation). It also supports the implementation of the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication (SSF Guidelines), especially in respect of climate change issues and livelihood improvement through enhanced value chains, post-harvest operations and trade building capacity of individuals, strengthening organizations and empowering women; reducing post-harvest losses and adding value to small-scale fisheries production; and facilitating sustainable trade and equitable market access (FAO, 2015; Zelasney *et al.*, 2020).

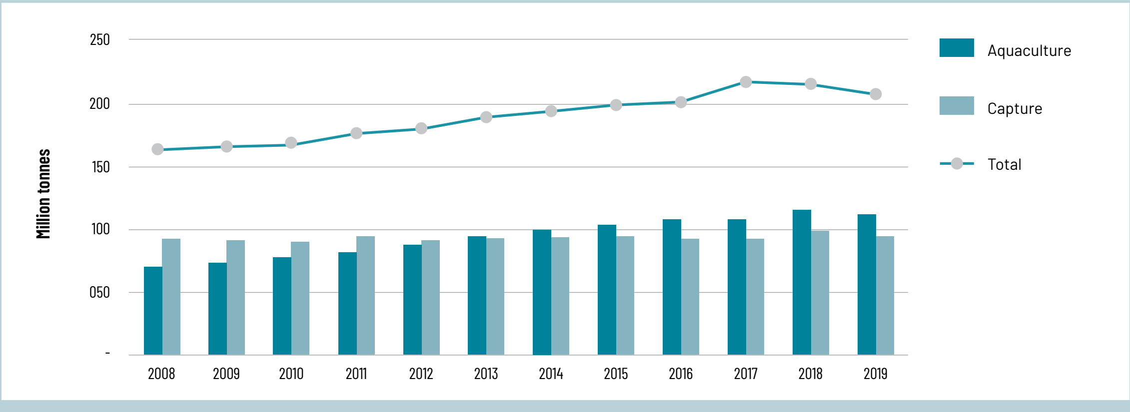
The report firstly provides data on global fisheries and aquaculture production, including disaggregated global production data by developing and developed countries. **Section 2** further identifies the main stages within a typical small-scale fisheries and aquaculture value chain. Based on these stages, the main processes where access to energy is critical are identified and through a review, the energy demand across the different stages of the value chain are linked. **Section 3** provides a broad overview of all renewable energy sources, after which **Section 4** identifies specific renewable energy interventions that could be deployed across the small-scale fisheries value chain. Thereafter, **Section 5** discusses the main technology specification and the costs of those technologies identified, and finally **Section 6** provides a conclusion and recommendation for the uptake of renewable energy technologies across the small-scale fisheries value chain.

1.1 THE FISHERIES AND AQUACULTURE SECTOR

The global fishing sector is a major source of nutrition and protein for the world. The global production of fish (fish, crustaceans, molluscs and other aquatic animals, excluding aquatic mammals, reptiles, seaweed and other aquatic plants) reached about 177.8 million tonnes in 2019, with 48 percent originating from aquaculture, and the remainder from capture fisheries. (FAO, 2020). Around 87 percent of the total production was used for human consumption, while the remaining 13 percent was used to produce non-food products (see **Figure 1**).

► FIGURE 1.

Global production of capture fisheries and aquaculture (2008–2019)



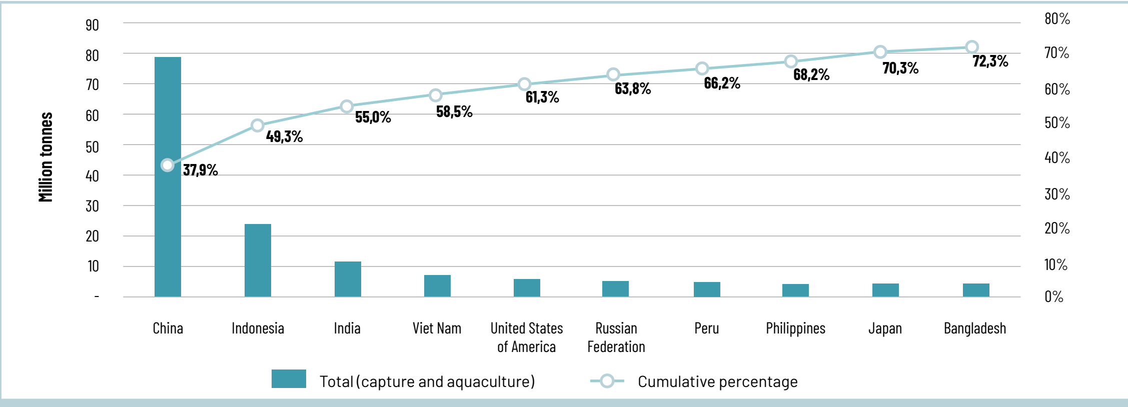
Source: FAO. 2021b. FAO fisheries statistics. In: FAO. Rome. Cited 31 January 2022. www.fao.org/fishery/statistics/home

Fish consumption accounts for 17 percent of the global intake of animal proteins, and 7 percent of all proteins consumed (FAO, 2020). This share increases in many coastal countries and islands. For instance, in countries such as Bangladesh, Cambodia, Ghana, Indonesia, Sierra Leone, Sri Lanka and several small island developing States (SIDS), fish constitutes more than 50 percent of the total per capita protein intake. Furthermore, the fisheries sector is a major employer in the global primary sector.

In 2018, an estimated 59 million people[1] (FAO, 2020) were engaged in fisheries and aquaculture. In developing countries, people engaged in fisheries and fish farming life are mostly small-scale fishers and fish farmers. In terms of national production, China, Indonesia, India, Viet Nam and the United States of America are the top five fish producing countries in the world; however, China leads the production of fish by a large margin, accounting for 37.9 percent of global fish production in 2019 (see Figure 2).

► FIGURE 2

Top ten fish producers (capture fisheries and aquaculture)

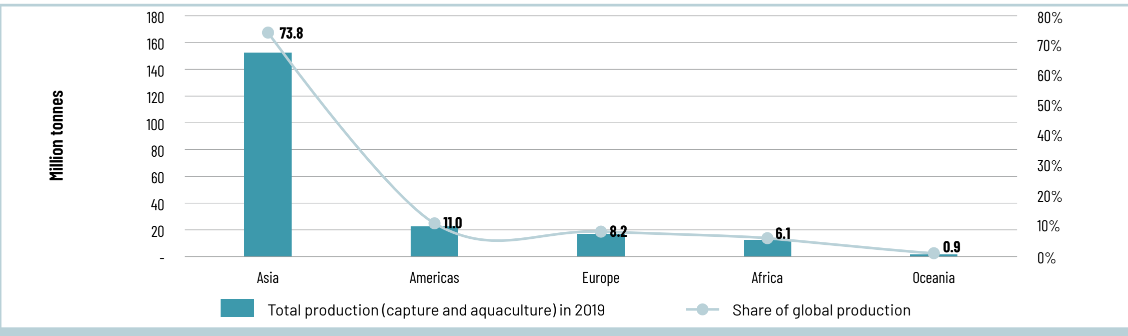


Source: FAO. 2021b. FAO fisheries statistics. In: FAO. Rome. Cited 31 January 2022. www.fao.org/fishery/statistics/home

Regionally, Asia accounts for a significant share of production (74 percent), followed by the Americas (11 percent), Europe (8 percent), Africa (6 percent) and Oceania (1 percent). Within Asia, China is the top producer of fish, accounting for almost 38 percent of global fish production (see Figure 3).

► FIGURE 3

Fish production by regions



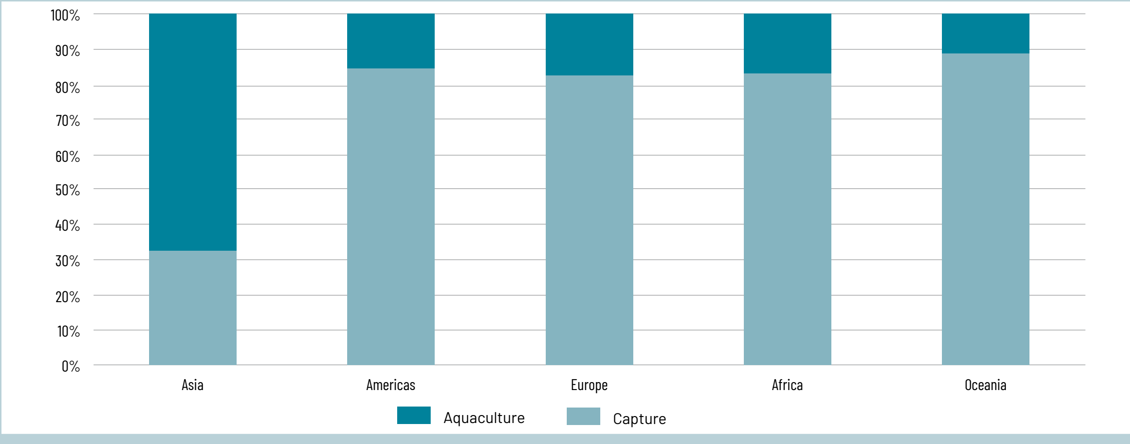
Source: FAO. 2021b. FAO fisheries statistics. In: FAO. Rome. Cited 31 January 2022. www.fao.org/fishery/statistics/home

[1] 20.53 million people were employed in aquaculture and 38.98 million in fisheries.

In 2019, more fish were produced globally from aquaculture than from capture fisheries (Figure 1). However, capture fisheries was regionally the primary method for producing fish. With the exception of Asia, where most fish are farmed and not caught, capture fisheries is the dominant fisheries production subsector in all other regions of the world. In Asia, almost 70 percent of fish is produced from aquaculture; in all other regions around 80 percent of fish are caught, while the remaining 20 percent are farmed (Figure 4).

► **FIGURE 4**

Share of fish production from capture fisheries and aquaculture across the regions



Source: FAO. 2021b. FAO fisheries statistics. In: FAO. Rome. Cited 31 January 2022. www.fao.org/fishery/statistics/home

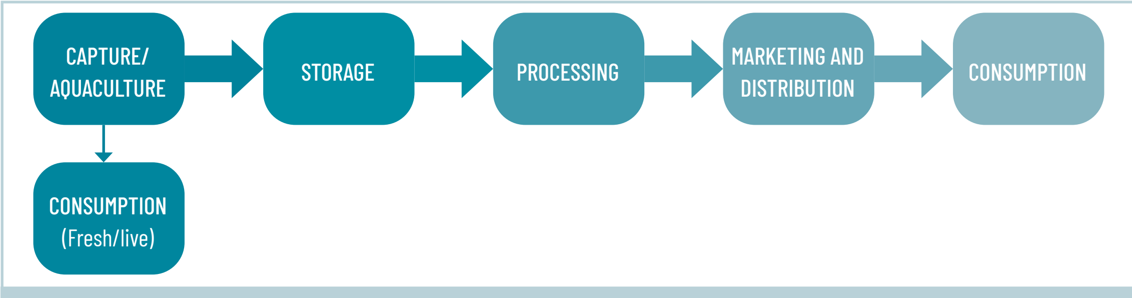
1.2 ENERGY USE IN FISHERIES AND AQUACULTURE

The fisheries and aquaculture sector, including fish production (capture fisheries and aquaculture), post-harvest processing, marketing and distribution, is highly dependent on the use of energy, particularly in the form of fossil fuels (FAO, 2015). The generic fish value chain[2] is formed by a series of interlinked activities that start from fish production up to fish consumption. Fish is produced either by direct capture or through aquaculture. After being produced, fish is either consumed directly or it goes through a series of other steps which include storage, processing, marketing, distribution and finally consumption. When stored, fish must be kept in a temperature-controlled environment and at the processing phase fish is processed into other products that are marketed and finally consumed. In the specific case of small-scale fisheries and aquaculture, fish is often directly sold to consumers immediately upon arrival or in markets close to aquaculture facilities. Even in these cases fish must be kept cold, often requiring the use of ice. Transport of the produce occurs throughout the value chain and between activities within the value chain. In sum, every step of the fish value chain requires energy, from production to consumption.

[2] This is a generic value chain and can vary across regions. Fish is often consumed fresh and in that case no processing is carried out.

► **FIGURE 5**

A simple depiction of a small-scale fish value chain



Source: Authors' own elaboration.

While energy is required at all stages of the value chain, the type of energy varies. For instance, oil and diesel are required to power vessels to catch fish, whereas at the storage stage, electricity is needed to power refrigeration equipment. As countries develop, energy consumption increases and this also holds true for the fisheries and aquaculture sector. While recent data is scarce, it was estimated that in 2000 the world's fishing fleets would be responsible for about 1.2 percent of total global fuel consumption, corresponding to 0.67 L of fuel per kg of live fish and shellfish landed (European Commission, 2020).Fuel use in vessels is a major source of GHG emissions and it was estimated that the world's fishing fleets consumed 40 billion litres of fuel in 2011, emitting 179 million tonnes of CO_2-eq (Parker *et al.*, 2018).

In small-scale fisheries, boats are very often not equipped with motors and access to modern refrigeration is rare or nonexistent. While the overall energy demand of small-scale fisheries is lower than it is for mid- to large-scale fisheries chains, it comes at the cost of less efficient operations, losses caused by inadequate storage facilities and overall reduced opportunities for small-scale fish farmers to increase economic output. Furthermore, energy is needed to produce ice to keep fish from spoiling. In areas where access to electricity is scarce, where grid electricity is only available intermittently, or where diesel generators are used to power ice making machines, the production and sale of ice are key entrepreneurial activities.

For storage, energy is needed to produce ice or to power refrigeration equipment. Small-scale fishers and fish farmers are generally dependent on ice to chill caught fish, while more affluent fish farmers and industrial fishers use refrigerators to store fish. Similarly, at the processing stage, energy is required for canning (electricity) or for drying and smoking (heat).

1.3 KEY ISSUES ON ENERGY USE

Small-scale fisheries and aquaculture are an integral part of the global fisheries and aquaculture sector. Nevertheless, small-scale fishers face several challenges related to access to technology, energy, infrastructure and connecting to markets. Energy is a key input required all along the fish value chain; it enables proper storage, processing, transport and marketing of fish produce.

While most developing countries aim to improve productivity and market access for small-scale fish value chains, there are a few key challenges that need to be overcome to ensure that the improvement in the value chains is environmentally sustainable and helps to confront climate change. The global fisheries sector contributes to and is impacted by climate change.

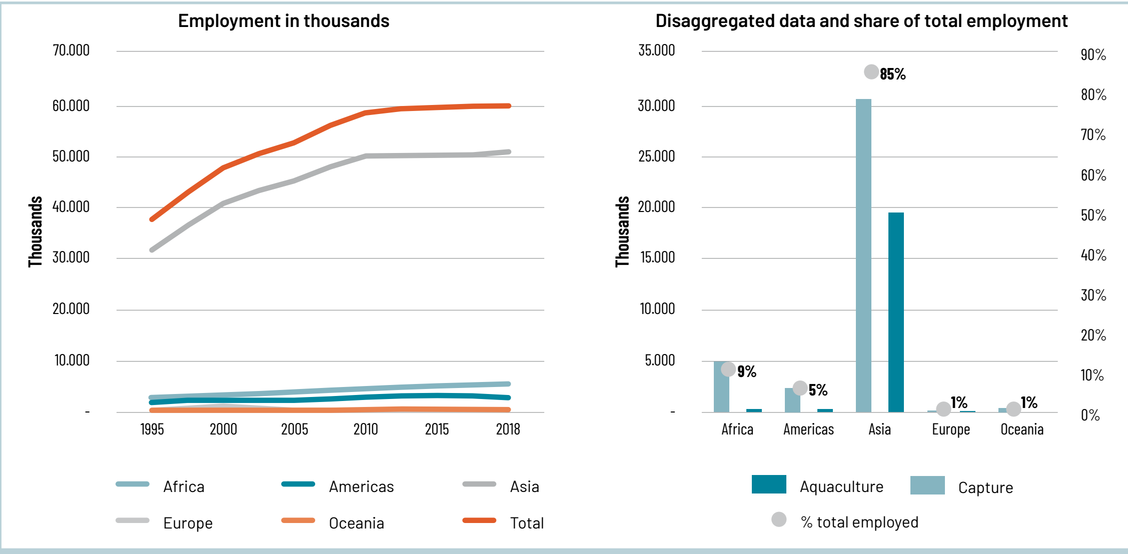
It is estimated that the fisheries sector consumed 40 billion L of fuel in 2011 and generated a total of 179 million tonnes of CO_2-equivalent GHGs, which is 4 percent of the emissions from global food production. It is worth noting that the bulk of fuel use is by the semi-industrial and industrial fisheries, rather than small-scale fisheries. Furthermore, emissions from the global fishing industry increased by 28 percent between 1990 and 2011 and the average emissions per tonne of fish landed grew by 21 percent over the same period (Parker *et al.*, 2018) with little coinciding increase in production (average emissions per tonne landed grew by 21 percent. As countries develop, energy consumption in the fisheries sector is expected to increase further. This represents a major challenge for ensuring that the increase in fish production is achieved in a way that does not increase GHG emissions. To this end, two major challenges emerge that are further analysed below.

1.3.1 MODERNIZING FISHERIES IN DEVELOPING COUNTRIES WILL INCREASE ENERGY DEMAND

According to FAO (FAO, 2020), global employment in fisheries has increased in the past three decades. The developing parts of the world have the highest share of population engaged in both aquaculture and capture fisheries (Figure 6). Furthermore, in developing regions the majority of those engaged in fishing and fish farming are in the small-scale sub-sectors (FAO, 2020).

► **FIGURE 6**

Employment in fisheries by regions



Source: FAO. 2020. *The state of world fisheries and aquaculture. Sustainability in action.* Rome. doi:10.4060/ca9229en

One of the characteristics of fishing is its dependence on fossil fuels and the resultant emission of GHGs. Fishing is considered the most energy-intensive food production method in the world. In India for instance, it has been estimated that direct fuel energy inputs to fishing typically account for a major share of 75 percent to 90 percent of total energy inputs of the sector. Considering the volumes at which fuel is consumed, it is essential that it should be addressed explicitly in future fisheries planning (Vivekanandan *et al.*, 2013).

Small-scale fisheries and aquaculture use relatively small production units with comparatively low input and low output. They have access to basic technology, limited access to modern energy and small capital investment. They are commonly managed on a family level, sometimes with a small group of employees, or at a community level. Fish is often sold in local markets but where fisherfolk are connected to larger markets and supply chains, it is also sold in national and international markets (FAO, 2020).

In many developing countries, the lack of access to energy and modern technologies prevents small-scale fisheries and aquaculture from operating efficiently and therefore increasing profits. One of the key aspects that can improve small-scale value chains is access to technology that assists fishers, fish farmers, processors and traders with keeping fish fresh for a longer period of time, thereby reducing fish losses. Improved storage options will provide more control over the timing of the selling process. Affordable and dependent access to ice and refrigeration, as well as processing and packaging technology, are important, but controlling temperature, processing and packaging are both energy-intensive processes.

In developing countries there is a need to expand cooling and processing infrastructure for fisheries, but if this expansion is based on fossil fuels there is a risk of increasing the already high GHG emissions originating in the agriculture sector. Renewable energy such as solar, wind, bioenergy and geothermal energy can be used to expand decentralized cold storage and processing infrastructure, as well as the production of capture fisheries and aquaculture.

1.3.2 LACK OF ENERGY AND COOLING LEADS TO HIGHER LOSSES

Fish is a highly perishable food and very susceptible to post-harvest losses resulting from inadequate handling during transportation, storage and processing. In most regions of the world, total fish loss and waste is between 30 percent and 35 percent (FAO, 2020). Fish loss occurs throughout the value chain, from catch or production to final consumption (Kruijssen *et al.*, 2020). Loss is influenced by several factors, including the species of fish, the associated physical characteristics (i.e. composition, weight and shape), the perceived value of the fish, volumes handled, the level of seasonality present and geographical location. Furthermore, fish enterprises in developing countries are likely to experience more losses than enterprises in developed countries during loading and unloading, processing, storage, transportation and marketing of fish. This is because of technical, financial, infrastructural and managerial constraints (De Silva, 2011). Spoilage and quality downgrading of the product is more likely to occur in lower-income economies due to high ambient temperatures; a lack of access to services, infrastructure and basic technology; a reliance on more traditional smoking and drying techniques for preservation; and lack of cooling (cold chain) facilities (HLPE, 2014). The lack of proper cold storage, cold chain transport and processing infrastructure is a major cause of fish loss. For example, 7.5 percent of all fish caught in the Amazon River in Peru is discarded upon landing because it has already decomposed. Furthermore, fish that suffer biological degradation due to suboptimal storage environments often fetch lower prices or are discarded. In Brazil, for example, unsold fish was found to have a 25 percent price decrease at the end of the first day. Fish that remained unsold after two days saw the price cut by a further 33 percent (Avdalov *et al.*, 2020). In Africa and Latin America, fish is mainly lost because of inadequate preservation infrastructure and expertise. Akande and Diei-Ouadi (2010) provide an insight into the losses affecting small-scale fisheries operators in sub-Saharan Africa.

Insufficient cooling can rapidly increase fish losses both in quality and quantity. Despite technical advances and innovations, many countries – especially the least developed economies –

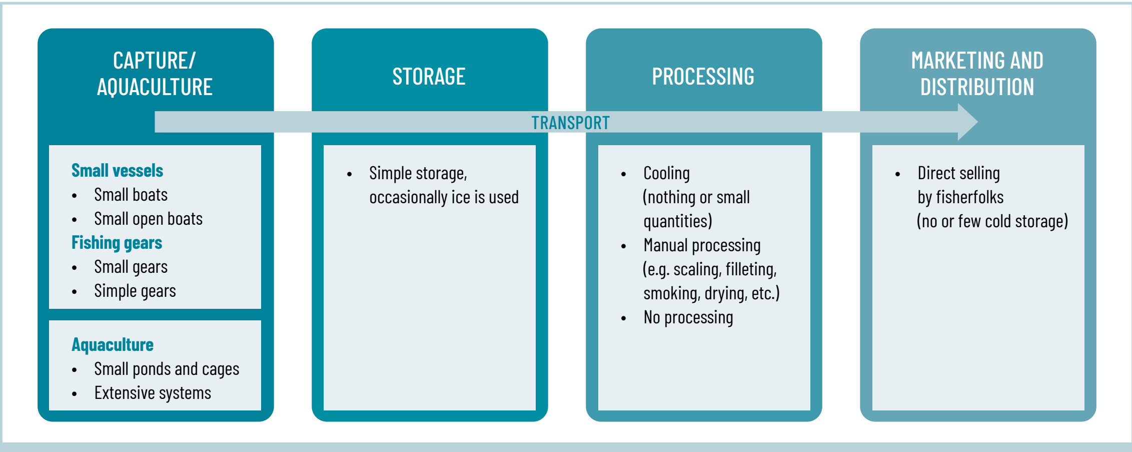
still lack infrastructure, services and practices for adequate onboard and onshore handling, and for preserving fish quality. Key deficiencies are related to access to electricity, potable water, roads, ice, cold storage and refrigerated transport. Effective fish loss and waste reduction requires the appropriate policies, regulatory frameworks, capacity building, services and infrastructure, as well as physical access to markets.

2. STRUCTURE OF AND ENERGY USE ALONG THE VALUE CHAIN

Small-scale fish value chains include all activities from pre-harvesting to harvesting to consumption. This includes the capture or harvesting of fish, storage, processing and marketing and sale of fish. The primary characteristic of the small-scale fish value chain is the kind of technology and equipment used. Activities are often conducted manually using low-cost technologies and often lack access to modern storage and processing technologies such as walk-in cold storage. The fact that small-scale fisheries and aquaculture can be performed by people who have limited access to these technologies, makes the value chain accessible to millions of people as a way of life. Figure 7 shows a typical small-scale fish value chain and the various technologies and processes used at each step.

► **FIGURE 7**

The structure of the various processes in a typical small-scale value chain

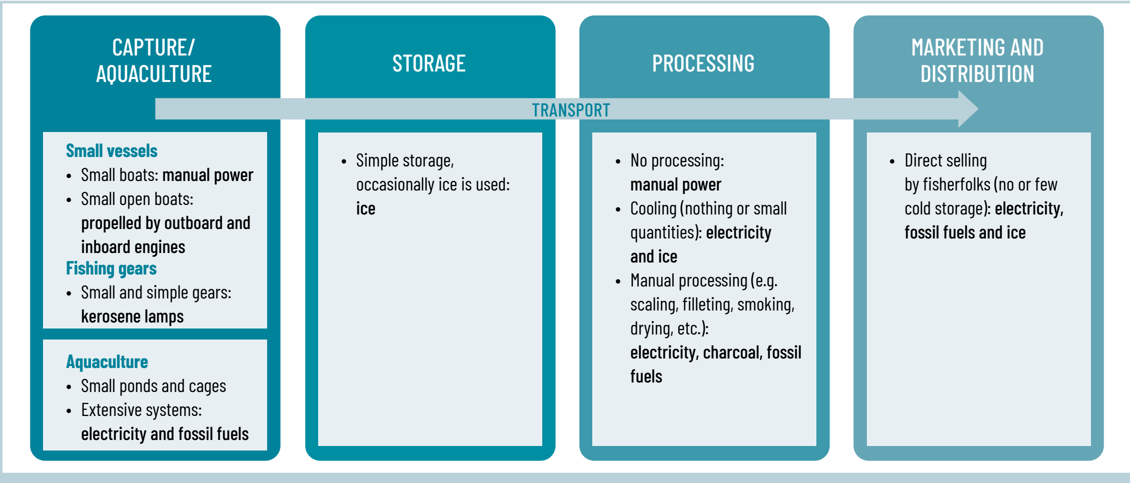


Source: Authors' own elaboration.

2.1 ENERGY USE AT EACH STAGE OF THE VALUE CHAIN

The small-scale fish value chain is characterized by the use of low technology, such as small boats for capture fisheries and small ponds or cages for aquaculture. After the first step of the value chain, the fish is often sold directly at the landing site. Limited storage infrastructure is available across the small-scale fish value chain, and ice is often used to keep the fish fresh in the markets and for transport over short distances. Processing mostly includes preservation practices such as drying, salting and smoking, after which the processed produce is either kept for self-consumption or is sold in local markets. Figure 8 details the main energy types used across the various steps of a typical small-scale value chain, corresponding to the stage-specific processes identified in.

► FIGURE 8
Energy used at each stage of a typical small-scale fish value chain

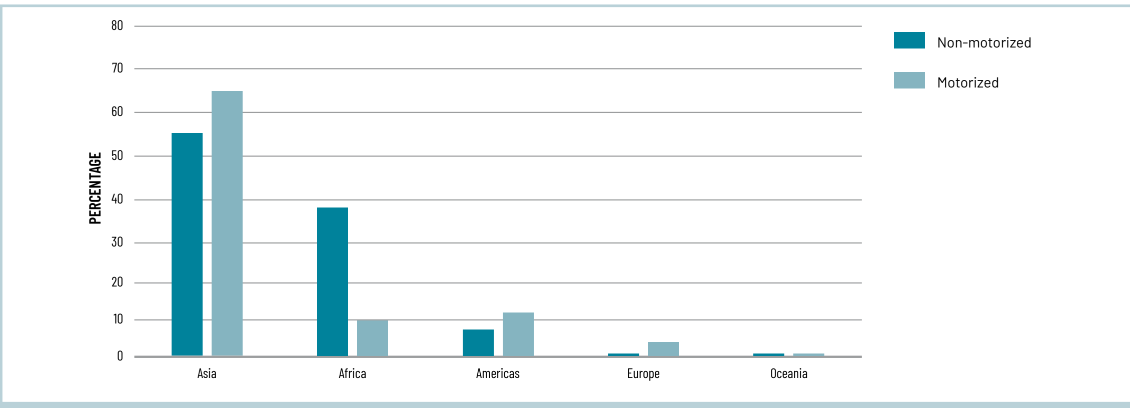


Source: Authors' own elaboration.

2.1.1 PRODUCTION STAGE

Small-scale fishers rely on relatively simple gear for fishing. In many cases, only shore-based fishing is conducted, using small fishing vessels that make short trips. Harvests are mainly destined for human consumption and are often sold on landing in the fish markets near the shore. A small proportion of the production is often kept for self-consumption. Fuel use is primarily associated with motorized vessels for running engines, or onboard equipment such as lamps and lights. Asia has the largest share (70 percent) of both motorized and non-motorized vessels in the world (FAO, 2020). In the developed regions of the world there are more motorized vessels than non-motorized, while in Africa non-motorized vessels are the primary vessels used for fishing (Figure 9).

► FIGURE 9
Share of motorized and non-motorized vessels across regions



Note: Totals sum to 100 percent across categories, not by region.

Source: FAO. 2020. *The state of world fisheries and aquaculture. Sustainability in action*. Rome. doi:10.4060/ca9229en

In 2018, the total number of fishing vessels globally was estimated to be 4.56 million. depicts the share of motorized and non-motorized fishing vessels across different regions of the world. In 2014, around 79 percent of the motorized vessels were less than 12 m in length overall (FAO, 2015) because small-scale fishing is generally performed on a daily basis within a coastal or lakeside zone, catching an average of 1 tonne to 3 tonnes of fish per person annually. On average, a small vessel operates for 100 days per year and uses around 2.7 tonnes of fuel annually (see Table 1).

► TABLE 1

Size of vessels and energy consumption

VESSEL SIZE CLASSES	NO. OF VESSELS	TOTAL INSTALLED kW	DAYS AT SEA PER YEAR	FUEL CONSUMPTION (tonnes)	
				PER VESSEL	PER VESSEL CLASS
>24 m	43 767	27 803 318	180	296.39	12 972 101
12–24 m	320 997	31 469 963	140	28.99	9 305 703
<12 m	2 157 888	33 716 479	100	2.7	5 826 298
Total	2 522 653	92 989 760			28 104 102

Source: FAO. 2015. *Fuel and energy use in the fisheries sector: Approaches, inventories and strategic implications*. FAO Fisheries and Aquaculture Circular No. C1080. Rome. www.fao.org/3/i5092e/i5092e.pdf

Small-scale aquaculture production is limited to extensive and semi-extensive systems where small ponds and cages are used to farm fish. The production of extensive and semi-extensive aquaculture varies from 0.5 tonnes/ha to 5 tonnes/ha and uses between 0 GJ/tonne to 25 GJ/tonne of fish produced (see Table 2).

► TABLE 2

Energy used in aquaculture production by type of aquaculture system

SYSTEM CATEGORY	CHARACTERIZED BY	ENERGY INPUTS PER TONNE OF PRODUCTION	
		GJ	TONNES FUEL EQUIVALENT
Extensive	Less than 0.5 tonne/ha per year for fish, but substantially more for molluscs or algae; use of natural waterbodies (e.g. lagoons, bays, embayments) and of natural, often unspecified, food organisms.	0	0
Semi-extensive	0.5 tonne/ha to 5 tonnes/ha per year; possible supplementary feeding with low-grade feeds; regular use of organic or inorganic fertilizers; rain or tidal supply; and/or some water exchange. Normally traditional or improved ponds: limited cage systems, some enclosures, rope-based mollusc culture (energy for vessels/handling).	25	0.5
Semi-intensive	2 tonnes/ha to 20 tonnes/ha per year; dependent largely on natural food, augmented by fertilization or supplementary feed; normally in improved ponds, some enclosures, or simple cage systems.	50	1.0

(Cont.)

SYSTEM CATEGORY	CHARACTERIZED BY	ENERGY INPUTS PER TONNE OF PRODUCTION	
		GJ	TONNES FUEL EQUIVALENT
Intensive	Up to 100 tonnes/ha per year; completely fed; usually ponds, tanks, raceways with water exchange, or cages.	75	1.5
Super-intensive	Up to or exceeding 1 000 tonnes/ha per year; completely fed, tanks, raceways with/out recirculation, or cages.	100	2

Source: FAO. 2015. *Fuel and energy use in the fisheries sector: Approaches, inventories and strategic implications*. FAO Fisheries and Aquaculture Circular No. C1080. Rome. www.fao.org/3/i5092e/i5092e.pdf

2.1.2 HANDLING AND STORAGE

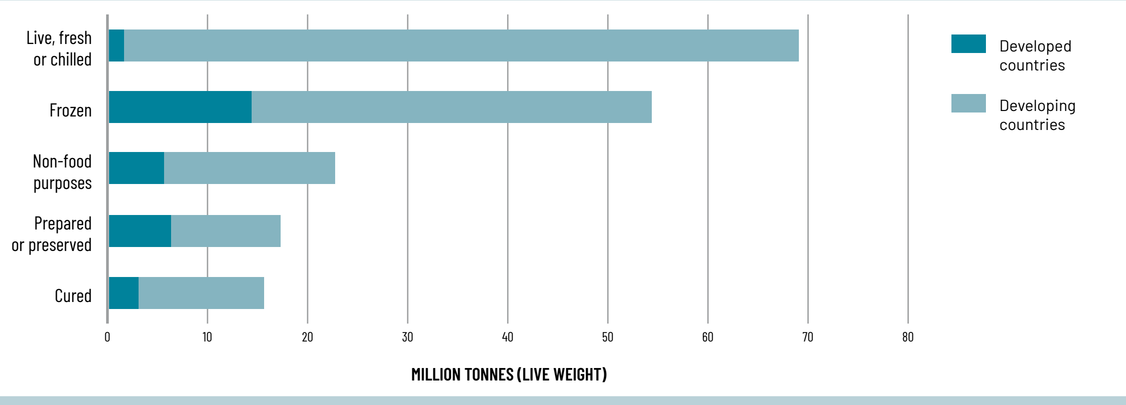
Once fish is caught or farmed, it needs to be stored in chilled or frozen form to avoid biological spoilage. Ideally, fish should be cooled on board the vessel as soon as it is caught. Over the past five decades, the fisheries industry has changed substantially due to an increased availability of technology, improvements in transport and storage infrastructure, and better access to freezing and cold storage. This has led to changes in the way that fish is stored, processed and finally consumed.

Fish is a highly perishable food and particular care is required at harvesting, and all along the supply chain, to preserve quality and nutritional attributes and avoid contamination, loss and waste. The availability of cooling/chilling infrastructure is a key factor in determining how fish is consumed. In developed countries with universal access to electricity and good availability of freezers, fish is predominantly frozen and then sold in formal markets. However, in developing countries where access to electricity and the availability of a cold chain is limited, fish is primarily consumed fresh or chilled. Ice is frequently used to chill fish before it is sold. Live, fresh or chilled fish still represent the largest share (44 percent) of fish utilized for direct human consumption and is often the most preferred and expensive form of fish. It is followed by frozen (35 percent), prepared and preserved fish (11 percent) and cured fish (10 percent).

In 2018, live, fresh or chilled fish still represented the largest share (44 percent) of fish utilized for direct human consumption (FAO, 2020). Furthermore, the majority of fish consumed in developing countries is either fresh or chilled. Consumption patterns across developing and developed countries have evolved significantly over time. In developed countries, the availability of electricity and equipment for freezing fish caused an increased consumption of frozen fish, which rose from 27 percent in 1960 to 58 percent in 2018. During the same period, the consumption of cured fish declined from 25 percent to 10 percent (see **Figure 10**).

► **FIGURE 10**

End use of global fish production by developing and developed countries in 2018



Source: FAO. 2020. *The state of world fisheries and aquaculture. Sustainability in action*. Rome. doi:10.4060/ca9229en

In contrast, fish continues to be consumed fresh in developing countries soon after landing, or harvesting from aquaculture, even though the share has declined from 62 percent in the 1960s to 51 percent in 2018. Nevertheless, the consumption of frozen fish in developing countries increased from 3 percent in 1960 to 31 percent in 2018. Furthermore, traditional forms of processing such as salting, fermentation drying and smoking, while still prevalent in many poorer developing countries, has declined over the last five decades. The use of such traditional ways of fish processing, which are used in particular in Africa and Asia, declined from 29 percent in the 1960s to 10 percent in 2018.

2.1.2.1 Importance of the cold chain

Globally, chilling or freezing fish products are the most widespread and important post-harvest processes and fresh, chilled and frozen fish represent the largest share of total fish consumption. Depending on the country and availability of resources and technology, freshly caught fish is ideally chilled or frozen.

- **Chilling**

  Fresh fish is generally consumed soon after capture. Chilling fish and other onboard cooling operations are usually performed on larger vessels that stay at sea for prolonged periods of time and have the engine capacity to power cooling equipment. In small-scale fisheries, ice is used on board and onshore to chill fish. The combination of increased fresh fish consumption and increased quantities of ice being used per unit of output has increased global ice use (FAO, 2015).

  The use of ice is also common in aquaculture, at the time of harvest and/or during initial post-harvest grading/packing stages. Thus, in most cases the cost of ice and the energy consumed to produce it are accounted for separately. As shown in Table 3, ice can be produced in different forms with approximately the same energy. While the cooling capacity of different types of ice is similar in weight terms, it differs based on changes in volume due to changes in densities. The cooling and melting rate vary based on its surface area. For example, the cooling capacity of flake ice is over four times that of tube ice because of the differences in surface and density. However, block ice is easily produced in developing countries, especially in rural areas where it is the most necessary. The ice is broken down before it is used for cooling fish.

► **TABLE 3**

Energy demand to produce ice in temperate and tropical regions

TYPE OF ICE	TEMPERATE REGIONS		TROPICAL REGIONS	
	kWh per tonne ice produced	Ice use per tonne fish	kWh per tonne ice produced	Ice use per tonne fish
Flake	50–60	1.3	70–85	1.7
Plate	45–55	1.3	60–75	1.7
Tube	45–55	1.4	60–75	1.9
Block	40–50	1.5	55–70	2.0

Source: FAO. 2015. *Fuel and energy use in the fisheries sector: Approaches, inventories and strategic implications*. FAO Fisheries and Aquaculture Circular No. C1080. Rome. www.fao.org/3/i5092e/i5092e.pdf

Moreover, ice can be placed in containers and chilling fish can also be carried out in cooling devices. Catering fridges and retail displays are useful for fish preservation and marketing but have a high energy demand, ranging from 200 GWh to 238 GWh and 288 GWh to 235 GWh, respectively (FAO, 2015). On a small scale these energy requirements and costs would not be accessible for some fish farmers, as they usually have low incomes and limitations when connecting these devices to an electricity grid.

- **Freezing**
  Freezing is one of the most important processing and preservation methods for fish because it stabilizes fish quality and slows down biochemical changes and spoilage. Frozen fish can be stored for months, depending on the species. The main freezing methods used are blast freezing, plate freezing and immersion or spray freezing. Freezing requires the removal of heat and during the first stage the temperature falls very rapidly to around 0 °C, the freezing point of water. Normally, plate freezing blocks or blast freezing is used; the latter is more common for larger, higher-value product. Modern blast freezers are highly efficient and give very rapid contact/performance output. These are typically linear in configuration, although spiral belt designs also used. Freezing 1 tonne of fish allows for freezer system efficiency, and requires some 120 kWh, which is USD 0.15/kWh, amounting to USD 18/tonne (FAO, 2015). After freezing, the frozen fish is placed in cold storage.
- **Cold storage**
  Frozen fish can be kept in cold storage for six months or more. Cold storage is used during the transport of frozen fish, as well as at the marketing and retail stages of the value chain. The energy demand for cold storage depends on storage time, building and insulation specifications, the difference between storage and ambient temperatures, and on the ways in which the storage is used. Table 4 provides an example of energy use in cold storage and refrigerated transport in the United Kingdom of Great Britain and Northern Ireland.

► **TABLE 4**

Energy use for cold storage and transport in the United Kingdom of Great Britain and Northern Ireland

COMPONENT	ESTIMATED ENERGY (GWh)	EQUIVALENT COST AT USD 0.15/kWh (USD million)
Cold stores	45	6.8
Refrigerated transport	241	36.2

Source: FAO. 2015. *Fuel and energy use in the fisheries sector: Approaches, inventories and strategic implications*. FAO Fisheries and Aquaculture Circular No. C1080. Rome. www.fao.org/3/i5092e/i5092e.pdf

It should be noted that traditional cold storage requires access to an electricity grid. However, such access can be unreliable or completely absent in the rural areas of many developing countries. In these cases, decentralized renewable energy can be used to power cold storage facilities. Decentralized solar cold storage facilities can be used to store frozen fish. This is discussed in the subsequent chapters.

2.1.3 PROCESSING

- **Fish drying**

In many parts of Africa and Asia, sun and active solar drying of fish, as well as smoking and salting, are important and traditional preservation methods associated with small-scale fisheries. Dried fish is one of the main processes of harvest fisheries. The drying process is performed to reduce the moisture content to 10 percent or less. Air speed over the surface of the fish, air temperature and air humidity are factors that affect moisture reduction efficiency (FAO, 2021c; Arason, 2003).

Technologies for drying fish are usually low-cost and use minimal service facilities. With adequate technology, fish loss and waste are reduced to around 50 percent, as drying fish on the ground and poor weather conditions can be managed (Kruijssen *et al.*, 2020; Griliopoulos, 2014; Ward and Jeffries, 2000).

Drying racks, mechanical dryers, and solar dryers are common technologies that can be used in rural or non-connected areas. Raised racks use the sun's energy to dry fish off the ground, which is a faster and cleaner method than drying on the ground. Mechanical dryers require electricity, combustion of wooden materials, and can be used in all weather conditions. Solar dryers capture the sun's energy on a rack-enclosed structure covered in polythene, which presents challenges for operating efficiency in poor weather conditions (FAO, 2021d; Lingayat, Balijepalli and Chandramohan, 2021).

- **Fish smoking**

Traditional fish "smoking" is a heating/cooking and drying process. Wood is burnt to produce the heat energy. Various designs of smoking chambers are used.

Smoking fish can extend shelf life from five to six months. It also allows for easier transport, helps to match supply with demand and reduce losses. However, fish smoking is an energy-intensive process. It needs enormous quantities of wood and when not used efficiently can also contribute to deforestation. In Cameroon for example, 3 000 of Cameroon's 400 000 hectares of mangrove forests are lost annually, primarily for fuelwood. Most of this (84 percent) is used to smoke fish (IIED, 2017).

While the use of wood for smoking is a challenge, the inefficient way in which wood is used to smoke fish is also problematic. In Cameroon for instance, traditional methods of smoking involve smoking fish over burning wood set between three stones. Because of this, almost 60 percent of the heat is lost during smoking, and heat distribution is so poor that 30 percent of the fish cannot be sold because it is undercooked (IIED, 2017). Improved smoking stoves can drastically reduce wood consumption and it is possible to diversify fuels by using other forms of biomass that are safe for smoking.

2.1.4 DISTRIBUTION AND MARKETING

For small-scale fisheries and the aquaculture value chain, the distance between production and marketing is relatively small. Fish produce is often sold immediately at landing sites or in local markets. Where refrigerated transport is available to large-scale, modern fisheries and the aquaculture value chain, with small-scale fisheries and aquaculture fish is often transported in boxes filled with ice. Moreover, at markets, ice is the predominant cooling agent used by shops and hawkers. In some cases, electricity powered freezers are used to freeze the fish, which allows for longer storage. Several of the technologies outlined in Section 2.1.2 (Handling and storage) can also be used to increase the availability of ice at the distribution and marketing stage.

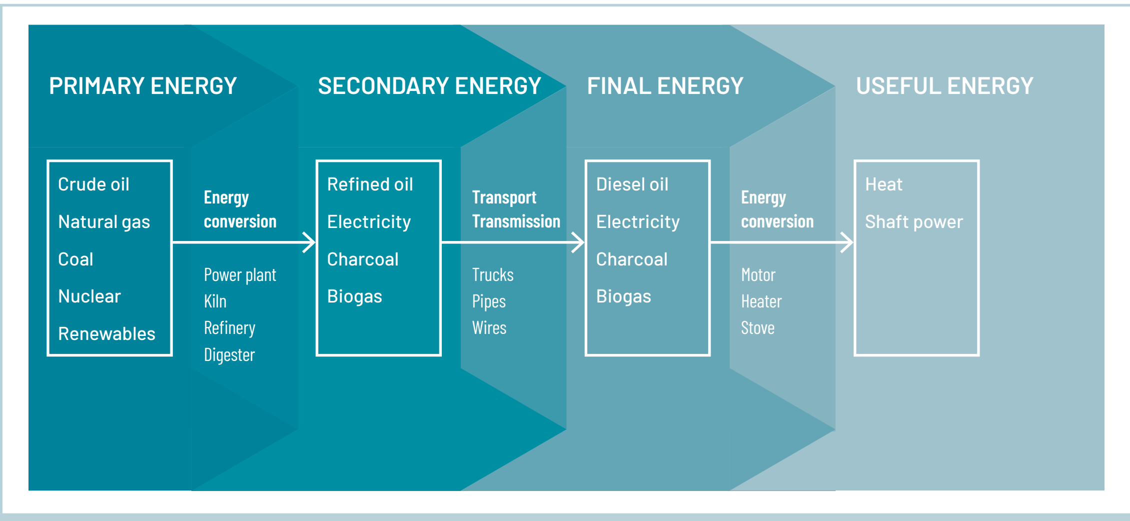
3. DESCRIPTION OF THE RENEWABLE ENERGY TYPES

3.1 INTRODUCTION TO ENERGY FORMS

Energy can exist in different forms and it passes through a number of conversion steps between its source and end-use. Primary energy is defined as energy that can be harvested directly from natural resources and includes fossil fuels (oil, coal and natural gas), nuclear energy and renewable energy sources (RES). Primary energy can be converted into more useful energy forms. Secondary energy is energy that is ready for transport or transmission, while final energy refers to the energy that end-users buy or receive. Lastly, useful energy is defined as energy used as an input in an end-use application. In some cases, primary energy can be the same as the secondary or even final energy (e.g. wood burnt for cooking purposes) (FAO, 1991; Øvergaard, 2008). A simple overview of different types of energy is provided in **Figure 11**.

▶ **FIGURE 11**

Types of energy



Source: FAO. 1991. *Basic energy concepts*. In: FAO. Rome. Cited 31 January 2022. www.fao.org/3/u2246e/u2246e02.htm#1.

3.1.1 ELECTRICITY

Electricity generation can occur both on a large and a small scale, as well as on- or off-grid, depending on the specific application. On-grid electricity can be generated at centralized power plants, as well as smaller units and is then transported through substations, transformers and transmission lines to the end-users (i.e. the consumers) (EPA, 2021a). Off-grid electricity generation can occur in remote locations, where production takes place in the vicinity of the consumption site, resulting in reduced energy losses during transmission, as well as reduced loads on utility transmission and distribution lines. It is also possible to have large-scale, off-grid electricity systems through the use of minigrids and microgrids. These are local, self-sufficient systems that can operate autonomously and are responsible for covering the energy requirements of a defined and limited area, such as a small community or a neighbourhood (Lantero, 2014).

The majority of electricity is produced using turbine-driven generators. In such a system, a moving fluid is required to provide the kinetic energy that is then converted into electrical power. Steam or gases from the combustion of fuels, water or air are widely used for this purpose (EIA, 2020a).

3.1.2 THERMAL ENERGY: HEAT

Thermal energy can be generated from the combustion of fuels and as a by-product of electricity production in combined heat and power (CHP) plants. It can be used for cooking purposes, as well as heating and cooling applications. Similar to electricity, thermal energy can be produced on a large or a small scale. In a decentralized (i.e. off-grid) system, heat is generated close to the consumption site and can be used for water heating purposes, as well as space heating for households and public buildings, ensuring access to thermal energy even in remote locations. Thermal energy installations can also be connected to district heating grids, which are responsible for distributing heat that is produced in a centralized location both for residential and commercial applications (Energypedia, 2017).

3.1.3 ENERGY SUPPLY AND DEMAND

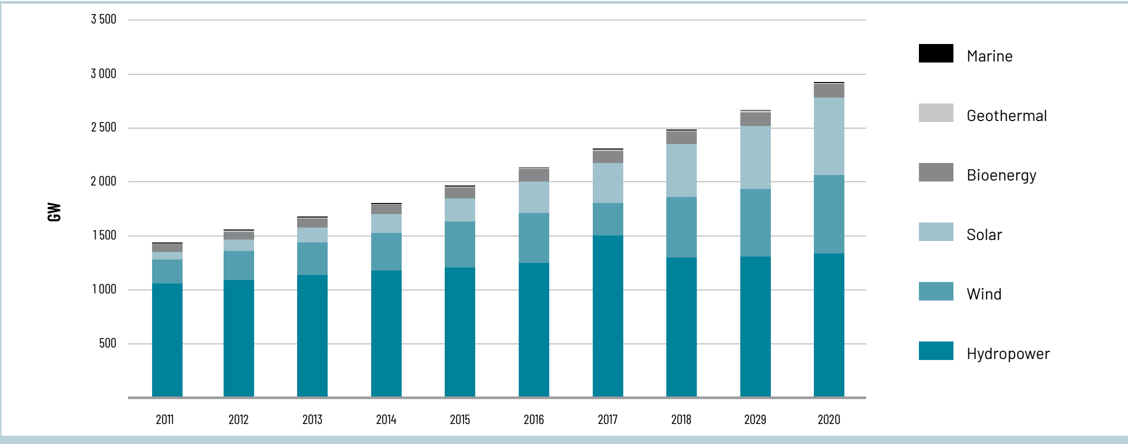
Energy demand is used to describe the amount of energy that is consumed by human activity, while energy supply refers to the amount of energy that is generated in various power plants. The energy demand is variable on an hourly and seasonal scale, depending on consumer behaviour. For example, during the summer months, consumption peaks in the afternoon due to the extensive use of air-conditioning, while in winter, consumption is higher in the morning and evening when temperatures drop and heating is required (EIA, 2020b). Additionally, in recent years the global energy demand has consistently risen due to population and economic growth, as well as more intensive industrial activities. Improving the efficiency of energy generation technologies and diversifying energy sources can play a vital role in achieving a more flexible power system, which at any given moment can match supply and demand in a timely and efficient manner (EIA, 2011).

3.2 RENEWABLE ENERGY SOURCES

Fossil fuels currently dominate the energy market and are responsible for approximately 80 percent of the world's energy supply. However, these types of resources are available in finite quantities and their depletion is a cause for concern. Additionally, their extensive use is responsible for more than 75 percent of human-caused harmful emissions over the past 20 years (United States of America Department of Energy, 2021a). RES have been attracting increasing attention because they offer an effective solution to reduce GHG emissions and meet the rising energy demand in a sustainable manner. RES include solar and wind energy, bioenergy, hydropower, geothermal energy and marine energy. The use of renewables over fossil fuels displays significant advantages, such as reduced air and water pollution, easy access to clean energy for everyone and an overall more resilient energy system. Renewable energy can be used in a variety of applications, such as electricity and heat generation, or production of fuels for transportation (REN21, 2019). Many countries have implemented policies to promote the use of renewable energy technologies, such as capital subsidies, feed-in tariffs and tax exemptions. The global installed capacity of RES is presented in Figure 12.[3] Hydropower is the most dominant RES, with nearly 1.5 TW of installed capacity in 2020. Solar and wind energy have been growing rapidly, due to technology developments and their constantly decreasing installation and operations and maintenance (O&M) costs, reaching an installed capacity of 714 GW and 733 GW respectively. Bioenergy and geothermal energy follow with 127 GW and 14 GW in 2020, while marine energy is still primarily in the research and development phase.

► FIGURE 12

Global installed capacity of renewable energy sources



Source: IRENA. 2021a. *Renewable capacity statistics 2021*. Abu Dhabi, IRENA. 300 pp.

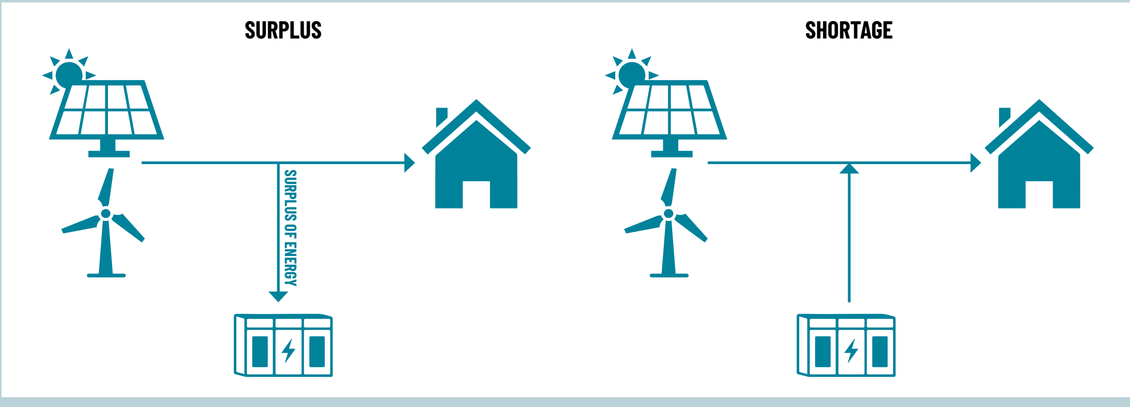
3.2.1 ENERGY STORAGE AND RENEWABLES

Despite their significant advantages, renewable energy systems such as wind and solar, have a variable electricity output due to the fluctuating nature of their resources. This causes shortages and surpluses of energy on hourly and daily timescales, where the system either fails to meet the electricity demand or surpasses it and thus the additional electricity is wasted. In order to balance loads, minimize losses and cover the energy requirements in an efficient manner, energy storage is required. Through energy storage technologies, it is possible to capture energy at a certain moment (i.e. when there is a surplus) and discharge it later to avoid potential shortages, thus making completely off-grid renewable energy systems possible (IRENA, 2017a). Generally, storage systems can provide reliability, but they also add to the complexity and overall investment and operating costs. An overview of the operation of a variable renewable energy and storage system is presented in Figure 13.

[3] Installed capacity is the maximum electricity production that can be achieved in a power plant under certain conditions, usually measured in MW or GW.

► **FIGURE 13**

Surplus versus shortage of energy with an energy storage system



Source: Authors' own elaboration.

Energy can be stored for short intervals of time or for long-term applications, depending on the storage technology used. Using batteries with renewable energy systems is one of the most promising and rapidly growing solutions for providing reliable electricity in isolated grids and off-grid communities, as well as ensuring the integration of renewables in the energy mix within a resilient and flexible grid. Currently, lithium-ion batteries are the most dominant technology because they offer a number of advantages. They feature a short charging time and high efficiency, while their lifespan ranges from 5 to 10 years (Smith *et al.*, 2017). A major disadvantage of lithium-ion batteries is their high cost, which in 2020 was approximately USD 137 per kWh (Statista, 2021). However, costs are constantly decreasing and by 2030 they are expected to be reduced to nearly 50 percent, due to technological advances and the optimization of manufacturing facilities and practices (IRENA, 2017b). Additionally, it is estimated that the performance and lifespan of battery storage systems will improve significantly in the near future.

3.2.2 SUSTAINABLE SITING FOR RENEWABLE ENERGY SOURCES

Locations with high resource availability are preferable for siting renewable energy systems because they offer significant potential for energy generation. There are usually few location restrictions for small-scale systems due to the small area required for their installation. On the other hand, identifying an appropriate site for a large-scale renewable energy installation can be a complex procedure, for which careful planning is required and a variety of parameters have to be considered in order to mitigate social and environmental impacts, while ensuring financial feasibility and optimal performance. In order to minimize negative effects on biodiversity and prevent landscape degradation, natural habitats, protected areas, archaeological sites and locations of cultural heritage have to be avoided. Terrain characteristics can affect the suitability of a certain site; for example, forests, mountainous areas and steep slopes can add to the complexity and cost of construction. Additionally, it is vital to avoid conflict with current land uses, while also complying with the regional and national legal requirements. Lastly, proximity to the existing infrastructure, such as roads and the transmission grid, can significantly improve the profitability of the installation (IHA, 2021a; Kereush and Perovych, 2017; Spyridonidou and Vagiona, 2020). The sustainable siting criteria can differ for each RES, according to its specifications and unique characteristics.

3.3 DESCRIPTION OF RENEWABLE ENERGY SOURCES

3.3.1 SOLAR ENERGY

Solar energy is energy emitted from the sun in the form of electromagnetic radiation and can be harnessed and converted into final energy forms, i.e. heat and electricity (Bharathi *et al.*, 2019). Two solar energy technologies that will be presented are photovoltaics (PVs) and solar heating systems.

- **Photovoltaics**
  PV or solar cells, are devices that can convert sunlight directly into electricity (EERE, 2021a). The individual solar cells are connected in order to create a PV panel or module. A solar power system consists of solar panels, a mounting structure and a DC–AC inverter. PV panels are categorized according to their power output (i.e. wattage), which usually ranges from 150 W to 400 W, depending on their size and efficiency. For electricity generation purposes, a number of panels are combined to create a solar PV system, of a size ranging from 5 kW to 10 kW in residential applications, up to hundreds of kW in commercial installations, to hundreds of MW in utility-scale power plants (i.e. solar farms). The typical dimensions of a residential 250 W PV panel are 165 cm x 100 cm, while for a 330 W commercial panel they are 196 cm x 100 cm (EcoDirect, 2021; SunPower, 2021).

  PV electricity can be produced both on-grid and off-grid and the size of the installation varies according to the specific application. PV panels are usually mounted on the ground, either in large- or small-scale configurations, while rooftop mounted systems are a very popular solution for electricity generation purposes in households and public or commercial buildings (IRENA, 2021b). Apart from ground-mounted PV modules, an innovative and emerging technology is floating solar panels. In this instance, panels are placed on platforms that float on bodies of water, such as reservoirs, lakes or even the sea surface (IFC, 2020). Lastly, small PV panels can be used to power different types of equipment and appliances, such as solar powered refrigerators, water pumps and lamps. Generally, an important advantage of solar derived electricity is its off-grid applicability, making energy access possible in remote locations. PV systems can be found in decentralized applications, either by providing electricity on a household scale, or by operating as part of microgrids used to cover the energy demands of small, remote communities.

  PV panels have a lifespan of approximately 25 years to 30 years, requiring minimal maintenance (SEIA, 2018). The vast majority of solar panels in the market are made of either monocrystalline or polycrystalline silicon, displaying a typical efficiency[4] that ranges from 18 percent to 22 percent, with a maximum theoretical value of 32 percent (EERE, 2019). Two other PV technologies that are gathering increasing attention are thin-film solar cells and III-V solar cells. The latter have an increased efficiency but are associated with significantly higher costs compared to other technologies (NREL, 2021a).

  Solar energy generation is also greatly affected by the intermittent nature of the solar resource, as energy production varies both during the day and throughout the year. This can result in surpluses and shortages of energy. In order to balance electricity loads and have a resilient system, energy storage (i.e. batteries) is required, especially for off-grid installations (EERE, 2021b).

- **Solar heating systems**
  Solar heating technologies are used to harness thermal energy from the sun, which can be utilized for hot water production or heating and cooling purposes on a residential, commercial and

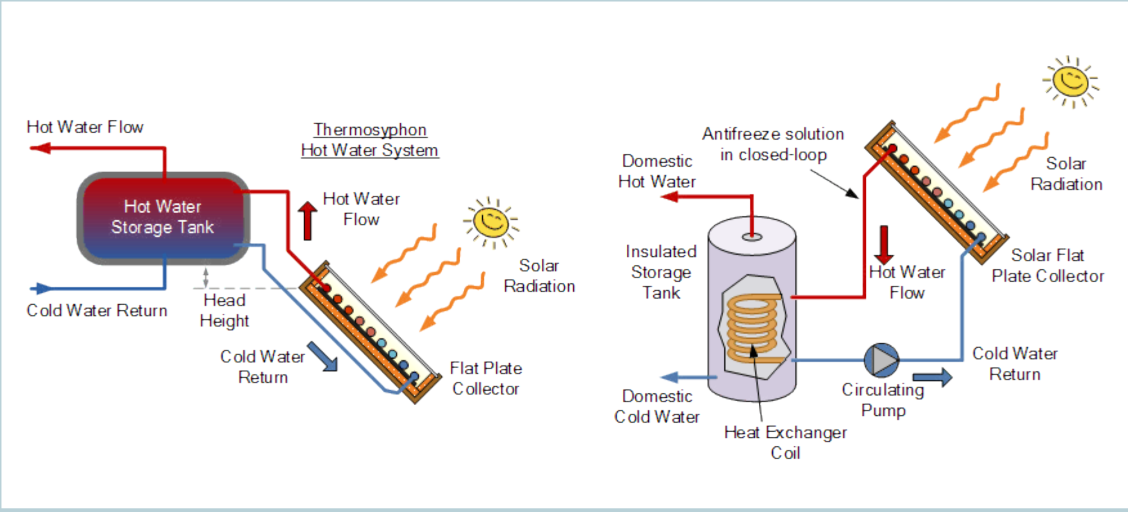
[4] Energy conversion efficiency is the ratio between the useful output of the system and the actual energy input.

industrial scale. A solar heating system consists of a solar collector, an insulated storage tank, a heat exchanger, a controller and the connecting pipes. The two most common types of solar thermal collectors are flat plate and evacuated tube collectors. The flat plate option is less expensive and more common, but evacuated tube collectors display higher efficiency and thus require less space to generate the same amount of heat (SEIA, 2018). The size of flat plate solar collectors is usually approximately 1.3 m x 2.4 m and can heat around 320 litres of water per day up to more than 70 °C (Alternative Energy Tutorials, 2021).

Solar heating systems can be classified as direct and indirect, based on the way that heat is transferred in the system. In a direct solar heating installation, water is heated through the solar collectors, then passes through the storage tank and can be used as a source of thermal energy. In indirect systems, a working fluid, which is usually a mixture of water and an antifreeze such as glycol, is used to transfer the heat. The fluid is heated in the collectors and then passes through a heat exchanger to provide thermal energy to the water inside the tank. After the liquid releases its heat, it flows back to the collectors to be reheated. A controller is used to ensure that fluid will flow to the collector when sufficient heat is available. An overview of the working principles in these types of systems is presented in Figure 14.

► FIGURE 14

Overview of direct and indirect solar heating systems



Source: Alternative Energy Tutorials. 2021. Flat plate collector. In: *Alternative Energy Tutorials*. Cited 31 January 2022. https://www.alternative-energy-tutorials.com/solar-hot-water/flat-plate-collector.html

Solar thermal energy can be produced both on a residential and a commercial scale. Household solar heating systems can be placed on rooftops or on the ground to provide hot water, as well as space heating and cooling. It is also possible to have larger configurations that will generate heat on a commercial scale, which can be distributed through district heating grids. Solar thermal energy installations can be applied very efficiently in remote locations, covering the demand for heat or hot water in numerous applications (Weiss and Spörk-Dür, 2021). The typical efficiency of a solar heating system is within the range of 50 percent to 75 percent, with a lifespan of 20 or more years (EERE, 2021c).

- **Factors affecting system output**

  Similar factors determine the performance of all solar energy systems (i.e. both PV and solar thermal installations). The output of such systems is greatly affected by the available solar resource, which is expressed with the global horizontal irradiance (GHI). GHI represents the amount of shortwave radiation received by a surface horizontal to the ground and is made up of the direct normal irradiance and diffuse horizontal irradiance. Additionally, solar energy potential relies on several location characteristics, such as latitude, terrain elevation and shading, the occurrence of clouds, as well as atmospheric moisture content and aerosol and dust concentration. Generally, the extensive presence of clouds and shading significantly reduces the electricity production of PV panels and heat generation from solar thermal systems (ESMAP, 2020). The orientation or tilt of a PV panel or a solar collector is another important variable, as maximum output can be achieved when the sun's rays are perpendicular to the normal of the module surface. In order to increase efficiency in PV installations, photovoltaic tracking systems are used, which allow for higher outputs but are also associated with higher costs (Seme *et al.*, 2020). Lastly, air temperature is a vital parameter for PV panels. Air temperature affects the electrical output of the system because it operates optimally at lower temperatures.

- **Siting and area requirements**

  In order to choose an appropriate location for a solar energy installation, a number of factors have to be considered and careful planning is required. Firstly, locations with abundant solar irradiation are preferrable because they display higher potential for both electricity and heat generation. Additionally, the shading of the site, as well as the tilt and orientation of the panels, are aspects that have to be taken into account to ensure the highest possible amount of direct sunlight on the surface of the equipment. In general, rooftop mounted panels have an important advantage compared to ground-mounted modules, as shading can be completely avoided. In the case of residential PV systems, the area required per panel is within the range of 1.3 m^2 to 1.7 m^2 (Energy Saving Trust, 2011), while for utility-scale solar power plants, approximately 3 ha of land are needed per MW of installed capacity (NREL, 2013; SEIA, 2021). Domestic solar heating systems typically use 3 m^2 to 5 m^2 of area to generate sufficient heat for household demands (CLASP, 2011). For solar district heating systems, large solar collectors are utilized, with an average area of 10 m^2 to 15 m^2. For each 1 m^2 of solar collectors, approximately 3 m^2 to 4 m^2 of land are required (Sørensen *et al.*, 2012).

- **Global potential and installed capacity**

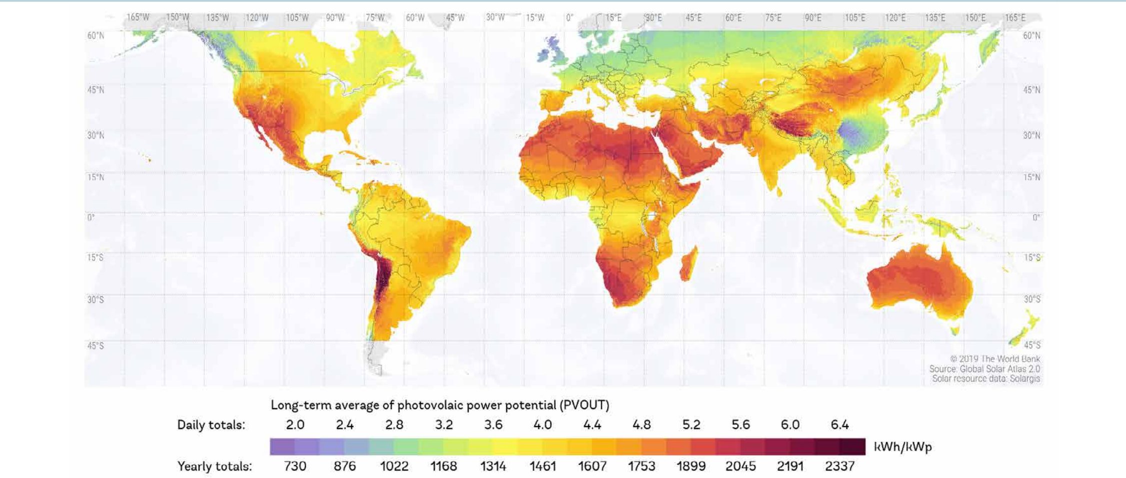
  The theoretical solar energy potential of a certain location is affected by the GHI. The technical solar PV potential PVOUT (kWh/kWp) is calculated based on the output of a typical PV system and is a measure of the average annual or daily power generation of the installation per unit of installed capacity. The calculations assume a large-scale installation with monofacial crystalline silicon PV modules fixed at an optimal tilt angle, while soiling losses are taken as 3.5 percent and losses related to interrow shading, mismatching, inverters, cables and transformers as 7.5 percent. The data for the estimation of the PVOUT were available at the Global Solar Atlas 2.0 (Global Solar Atlas, 2021a).

  The global technical PV potential is presented in **Figure 15**. As described in the legend of the map, areas marked with a purple and green colour indicate lower solar energy potentials, with the yearly average PVOUT varying from 700 kWh/kWp to 1 200 kWh/kWp. In comparison, yellow and orange coloured regions have a higher potential and their annual PVOUT is within the range of approximately 1 300 kWh/kWp and 1 900 kWh/kWp. The red and dark red coloured areas display the most promising results, where the yearly average outputs reach more than 2 300 kWh/kWp.

It can be seen that Africa and Australia display significant potential for solar energy, with Near Eastern countries showing similarly favourable conditions. Additionally, both North and South America have annual average PVOUT that can surpass 1 800 kWh/kWp in certain areas.

► FIGURE 15

Global long-term average of photovoltaic power potential



Note: Final boundary between the Sudan and South Sudan has not yet been determined.

Source: Conforms to UN. 2023. Map No. 4170, Rev. 19. Global Solar Atlas. 2021a. World solar resource map – photovoltaic power potential. In: *Global Solar Atlas*. Cited 1 March 2022. https://globalsolaratlas.info/download/world

Currently, more than 700 GW of PV systems are installed on a global scale – the installed capacity per region is shown in Table 5. In 2020, the most successful region in terms of solar PV deployment was Asia, where the installed capacity amounted to approximately 409 GW. Europe and North America follow with PV capacities of approximately 163 GW and 85 GW, respectively. The installed capacities in Oceania, South America and Africa range between 10 and 20 GW per region, while in Central America and the Caribbean they are around 2.3 GW.

► TABLE 5

PV installed capacity per region in 2020

REGION	INSTALLED CAPACITY IN 2020 (MW)
Asia	408 677
Europe	163 192
North America	84 557
Oceania	17 706
South America	12 770
Africa	10 637
Eurasia	8 227
Near East	8 093
Central America and Caribbean	2 293

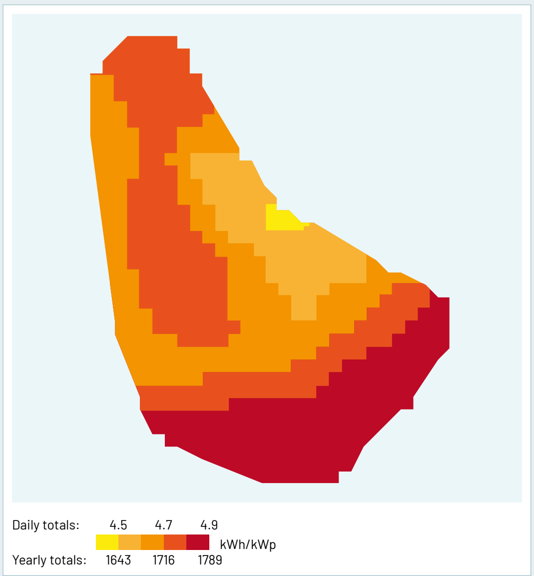
Source: IRENA. 2021a. *Renewable capacity statistics 2021*. Abu Dhabi, IRENA. 300 pp.

► BOX 1

Solar energy case study: Barbados

Barbados is addressing the challenges related to fossil fuels by utilizing its abundant solar resources and has become one of the most successful countries in the Caribbean regarding the integration of solar energy. In 2018, RES accounted for 5.8 percent of the total final energy consumption in the country, out of which 21 percent was sourced from solar energy and the remainder from the traditional use of biomass.[1] The country shows significant solar energy potential, as presented in the **Figure** below. The annual long-term average PVOUT in Barbados ranges from 1 600 to 1 800 kWh/kWp, with the highest potential in the provinces of Saint Philip and Christ Church.

Long-term average of solar PV potential in Barbados (1999–2018)



Source: Conforms to UN. 2023. Adapted from United Nations Geospatial, Wednesday, 20 May 2020. Global Solar Atlas. 2021b. Barbados solar resource map – photovoltaic power potential. In: *Global Solar Atlas*. Cited 1 March 2022. https://globalsolaratlas.info/download/barbados

The solar water heating (SWH) industry in Barbados emerged in the early 1970s, in response to a threefold increase in fossil fuel prices in one year. Since then, the sector has grown significantly and presently approximately half the households across the island use solar water heaters. In 2012, more than 50 000 SWH systems were used on the island.[2] Furthermore, in recent years Barbados has made an effort to strengthen its PV sector. In 2020, the installed capacity of PV systems was 50 MW, while the production in 2019 was approximately 44 GWh.[3]

Barbados aims to further increase the share of renewables in its energy mix and become fossil free by 2030. The implementation of several policy instruments supporting the deployment of solar technologies, most of which are focused on SWH systems, are essential for the country's current status. The Government Purchase of SWH for State Housing, established in 1977, has been supporting the growing SWH industry by mandating the installation of SWHs in newly-built government housing developments, while the Amended Homeowner Tax Benefit of 1996 allows an annual tax deduction of USD 1 750 for home improvements related to energy and water saving measures and the integration of SWH systems. The Fiscal Incentives Act (1974) prescribes a discount on SWH materials and imposes a 30 percent consumption tax for electric water heaters.[4] Lastly, regarding PV solar systems, the country has secured loans, including a USD 30 million loan from the Inter-American Development Bank in 2019, to financially support the installation of solar PV systems on both residential and commercial buildings.[5]

Notes

[1] IRENA. 2021c. Wind energy. In: IRENA. Cited 31 January 2022. www.irena.org/wind
[2] ETI (Energy Transition Initiative Islands). 2015. Solar hot water heater industry in Barbados. In: ETIEERE. Washington, DC, US Department of Energy. Cited 1 March 2022. www.energy.gov/sites/default/files/2015/03/f20/phase3-barbados.pdf
[3] IRENA. 2021b. Solar energy. In: IRENA. Cited 31 January 2022. www.irena.org/solar
[4] IEA (International Energy Agency). 2012. Fiscal Incentives Act. In: IEA. Cited 1 March 2022. www.iea.org/policies/5288-fiscal-incentives-act?country=Barbados&qs=bar&technology=Solar%20thermal%20electricity%2CSolar%20thermal%20heaters%2CSolar%2CSolar%-20PV&topic=Energy%20Efficiency%2CRenewable%20Energy and IEA (International Energy Agency). 2013. Homeowner Tax Benefit. In: IEA. Cited 1 March 2022. www.iea.org/policies/5289-homeowner-tax-benefit?country=Barbados&qs=bar&technology=Solar%20thermal%20electricity%2CSolar%20thermal%20heaters%2CSolar%2CSolar%20PV&topic=Energy%20Efficiency%2CRenewable%20Energy
[5] Iles, S. 2021. Facts about renewable energy in Barbados. In: The Borgen Project. Cited 1 March 2022. https://borgenproject.org/renewable-energy-in-barbados/

3.3.2 WIND ENERGY

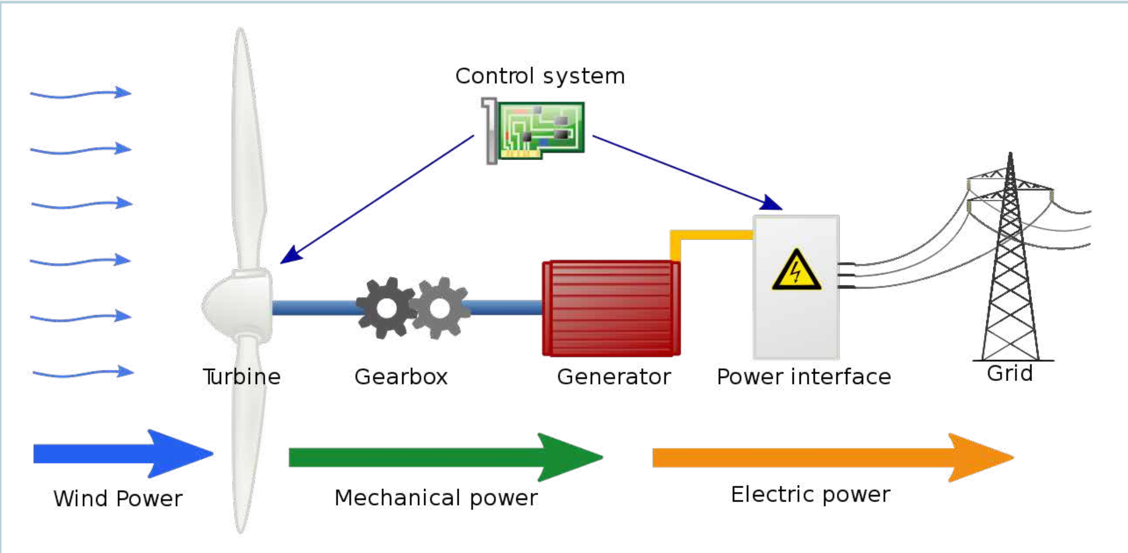
The kinetic energy of wind provides mechanical power to a wind turbine, which in turn transforms it into electricity through a generator (IRENA, 2021c). This mechanical power can also be used directly for specific tasks, such as water pumping or aeration purposes. The operating principle, as well as the main parts of a wind turbine, are presented in Figure 16.

Wind-derived electricity can be produced both on-grid and off-grid, with the installation size depending on the application. Small wind turbines, with sizes typically ranging from 400 W to 100 kW, are used to cover the energy demands of households or commercial buildings. It is possible to have even smaller wind turbines (i.e. micro-turbines) that are used as auxiliary power generators for boats and refrigeration units. Typically, the hub height of small turbines is within the range of 15 m to 50 m, and the diameter of the blades extends to approximately 20 m to 30 m (CANWEA, 2008).

Large commercial wind turbines can be more than 5 MW in size, with the hub height and rotor diameter surpassing 100 m in many cases. Large-scale wind electricity generation usually occurs in wind farms, where a group of wind turbines is placed in the same location to generate electricity on a MW scale (i.e. up to tens of MW). Generally, the size of a wind turbine increases along with the installed capacity, as seen in Table 6.

► **FIGURE 16**

Schematic overview of a wind turbine and its operation



Source: Adapted from Jalonsom. 2016. Wind turbine schematic.svg. In: Wikimedia Commons. Cited 31 January 2022. https://commons.wikimedia.org/wiki/File:Wind_turbine_schematic.svg and Nordmann, A. 2007. Wind turbine int.svg. In: Wikimedia Commons. Cited 31 January 2022. https://commons.wikimedia.org/wiki/File:Wind_turbine_int.svg

► **TABLE 6**

Effect of wind turbine installed capacity on hub height and rotor diameter

INSTALLED CAPACITY (kW)	HUB HEIGHT (m)	ROTOR DIAMETER (m)
2	6	3.5
50	25	15
300	34	40
2 000	80	72
5 000	100	112
8 000	150	168

Source: CANWEA. 2008. *Small wind turbine purchasing guide off-grid, residential, farm & small business applications*. Ottawa, Canadian Wind Energy Association. www.canadianpoultrymag.com/images/stories/small_wind_purchasing_guide.pdf and Cheggaga, N. & Ettoumi, F.Y. 2011. A neural network solution for extrapolation of wind speeds at heights ranging for improving the estimation of wind producible. *Wind Engineering*, 35(1): 33–53. https://doi.org/10.1260/0309-524X.35.1.33

Most wind turbines are located on land in onshore wind installations, while it is also possible to mount micro-wind turbines on the roofs of buildings as an auxiliary source of electricity. In recent years, wind farms constructed in the ocean or other bodies of water have garnered increased attention. Such installations are called offshore wind farms and they offer several advantages, such as stronger and more constant wind resource, resulting in an overall higher power output potential. However, their overall cost is higher because more complex infrastructure and maintenance is required (EERE, 2021d).

Wind turbines have a conversion efficiency within the range of 30 percent to 50 percent, with a maximum theoretical value of 59.3 percent, which is called the Betz limit (CSS, 2020). The lifespan of a wind turbine is approximately 20 years to 25 years, while maintenance is required every six months to ensure its efficient operation (EPA, 2013). Due to fluctuations of the wind resource, electricity production from wind turbines varies throughout daily and seasonal timescales, resulting in shortages and surpluses of energy. When coupled with an energy storage device (i.e. batteries), wind can provide a steady power output and become a more reliable energy source. This, however, leads to an increase in the installation and maintenance costs of the overall system.

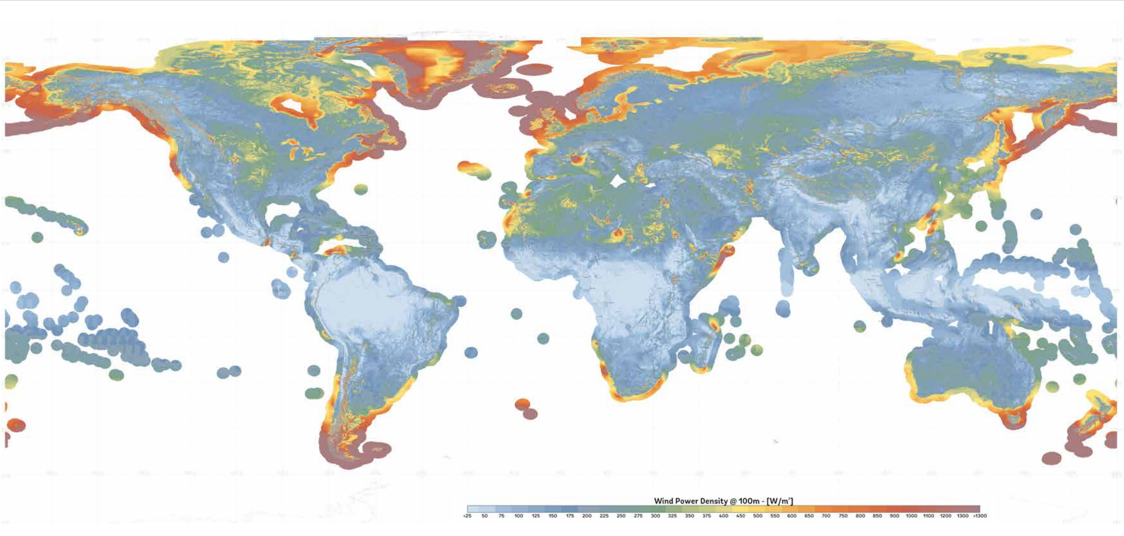
- **Factors affecting system output**

  The electricity generation of a wind turbine depends on a number of factors, such as wind speed, the wind power density and the characteristics of the chosen turbine. Wind speed is affected by the air density, the orography of the region, the time of the year and the altitude of the site. Generally, higher wind speeds are indicative of a larger wind energy potential, as more electricity can be generated. Turbines are designed to operate within a specific wind speed range and the respective lower and upper limit is called cut-in and cut-out speed. The wind power density is the mean annual power available per swept area (size of the area through which the rotor spins) of a wind turbine. The power output of a turbine increases cubically with wind speed (IRENA, 2021c). Lastly, the characteristics of the wind turbine, such as the hub height, rated power and rotor diameter, affect the electricity production of the system. Typically, a higher hub height and larger swept area mean that more power can be captured from wind.

- **Siting and area requirements**
  In order to achieve the optimal operation of a wind energy system, several parameters have to be considered. Strong winds, with a steady and uninterrupted flow, are vital to ensure high electricity production. For residential small-scale wind energy systems, optimal operation can be achieved with the correct siting of the turbines. They have to be sited upwind from any obstacles, such as trees and buildings, and should be approximately 10 m above anything within a 100 m radius (United States of America Department of Energy, 2021b). In the case of wind farms, area requirements take into account both the wind turbines, as well as the supporting infrastructure (i.e. roads, substations). For onshore wind farms, it is estimated that approximately 34.5 ha of land are required per MW of installed capacity (Denholm *et al.*, 2009), while in offshore installations, the area needed is lower at 14 ha per MW (Borrmann *et al.*, 2018).

- **Global potential and installed capacity**
  The global wind energy potential is expressed with the wind power density, which is depicted with a map in **Figure 17**. The blue coloured areas in the map have the lowest wind energy potential, as the mean wind power density at 100 m is lower than 200 W/m^2. Similarly, green and orange areas display higher potentials, with the wind power density ranging from 250 W/m^2 to 600 W/m^2. The areas marked with a red or purple colour have the highest potential, indicating wind power density at 100 m being higher than 1 200 W/m^2. Generally, coastal areas in northern Europe, South America, Asia and Oceania display high wind power densities, i.e. the highest wind energy potential. The northern part of Africa, where the mean wind power densities range from 350 W/m^2 to 800 W/m^2, displays higher potential compared to the rest of the continent.

► **FIGURE 17**
Global wind power density at 100 m



Source: Conforms to UN. 2023. Map No. 4170, Rev. 19. Global Wind Atlas. 2021a. World wind resource map – wind power density potential. In: *Global Wind Atlas*. Cited 1 March 2022. https://globalwindatlas.info/download/high-resolution-maps/World

In 2020 the overall installed capacity of wind power plants reached 730 GW globally. Asia has the highest share with 332 GW, as shown in **Table 7**. Europe and North America follow with approximately 207 GW and 140 GW, respectively, while the installed capacity of wind power plants in South America was around 25 GW. In the other regions there are less than 10 GW of wind energy installations per region, while in the Near East there is only 920 MW.

► TABLE 7
Wind energy installed capacity per region in 2020

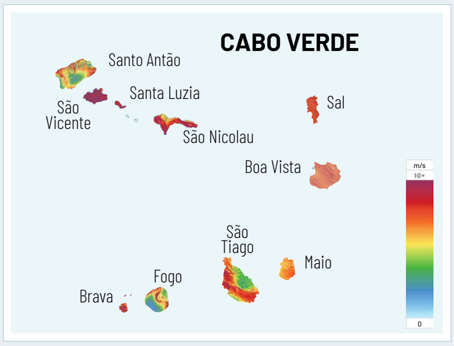
REGION	INSTALLED CAPACITY IN 2020 (MW)
Asia	332 253
Europe	207 560
North America	139 448
South America	24 493
Eurasia	9 867
Oceania	9 442
Africa	6 496
Central America and Caribbean	1 931
Near East	920

Source: IRENA. 2021a. *Renewable capacity statistics 2021*. Abu Dhabi, IRENA. 300 pp.

► BOX 2
Wind energy case study: Cabo Verde

In 2018, approximately 23 percent of the total final energy consumed in Cabo Verde came from RES. Wind energy accounted for 16 percent of that, solar energy for 2 percent, while traditional biomass accounted for the remaining 82 percent. The installed capacity of wind energy and solar energy installations in the country was 28 MW and 8 MW, respectively.[1]

Mean wind power density at 100 m in Cabo Verde



Source: Conforms to UN. 2023. Adapted from Map No. 4533, October 2014. Global Wind Atlas. 2021b. Cape Verde wind resource map. In: *Global Wind Atlas*. Cited 01 March 2022. https://globalwindatlas.info/area/Cape%20Verde?download=print

Cabo Verde has high wind energy potential, as the mean wind power density is higher than 400 W/m^2 across the country, increasing to around 900 W/m^2 in certain locations, such as Sao Vicente and Sao Nicolau (see the Figure). It is also estimated that the nine islands of the country could support the installation of approximately 240 MW of wind power plants, which is greater than the entire existing national power system of 150 MW.[3]

Wind power generation in Cabo Verde is intertwined with the Cabeolica wind farm, which started operating in 2011 and provides approximately 20 percent to 25 percent of the country's electricity. The overall installed capacity is 28 MW, and the farm consists of more than 30 turbines of 850 kW, set over four islands, namely Sao Vicente, Santiago, Sal and Boa Vista.[3] Each island has varying power capacity ranging from 4 MW to 10 MW, generating collectively more than 100 GWh per year.[4]

(Cont.)

This is the first commercial-scale wind farm in sub-Saharan Africa developed through a public–private partnership. The project was financed with a USD 42 million loan provided by the European Investment Bank and an additional USD 21 million loan supplied by the African Development Bank.[5]

Despite the advantages related to national energy supply from a renewable source, various problems have arisen with the efficient operation of the Cabeolica wind farm. For example, only 75 percent of the electricity produced from the wind farm is typically absorbed by the utility grid, due to insufficient storage and transmission infrastructure. Thus, additional wind energy growth on the islands will require investments in grid infrastructure and management and/or the development of energy storage solutions.[6]

The government of Cabo Verde aims to achieve a penetration rate of 50 percent for renewables by 2030. In this regard, the ECOWAS Centre for Renewable Energy and Efficiency was established in 2009 with the support of the ECOWAS Commission and international financial and technical support. Its main goals include the social and economic development of the country in a sustainable manner, focusing on the integration of RES and improving the efficiency of energy systems.[7]

Notes

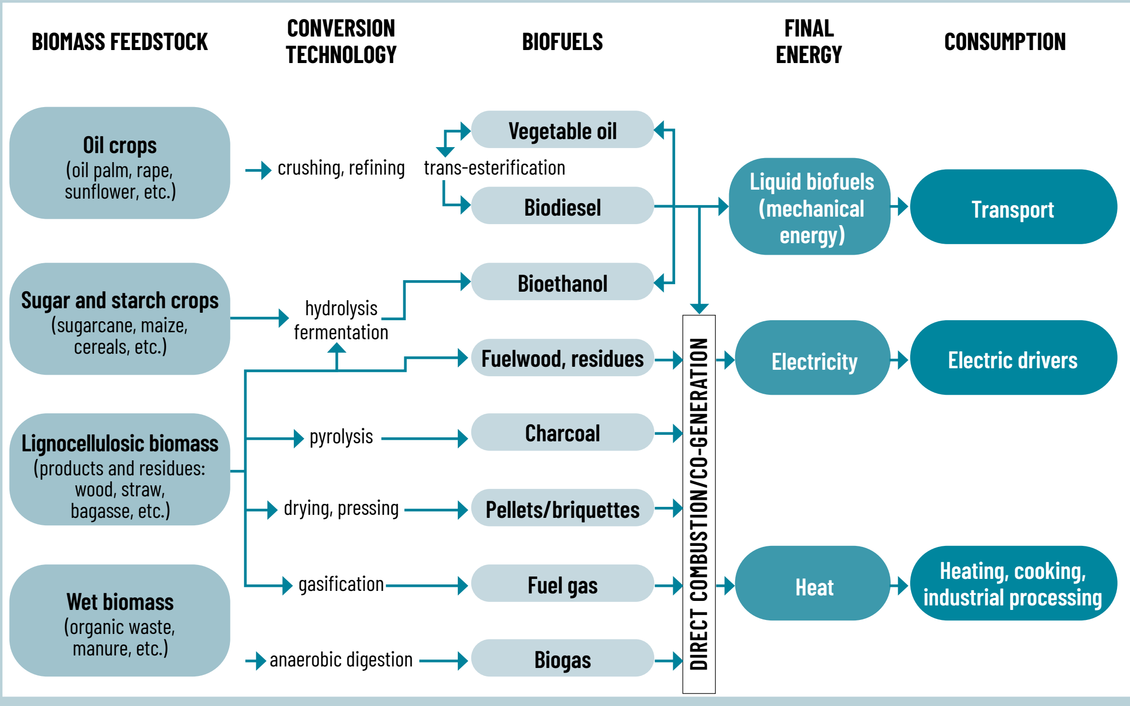
[1] IRENA. 2018. Country Profile - Cabo Verde. In: *IRENA*. Cited 1 March 2022. www.irena.org/IRENADocuments/Statistical_Profiles/Africa/Cabo%20Verde_Africa_RE_SP.pdf
[2] Nordman, E., Barrenger, A., Crawford, J., McLaughlin, J. & Wilcox, C. 2019. *Options for achieving Cape Verde's 100% renewable electricity goal: A review*. Island Studies Journal, 14(1): 41–58. https://doi.org/10.24043/isj.73
[3] ELEQTRA. 2021. Cabeolica Wind – Cape Verde. In: *ELEQTRA*. Cited 1 March 2022. https://eleqtra.com/projects/cabeolica-wind
[4] AfDB. 2020. Cape Verde. Cabeólica wind power project cost. In: *AfDB*. Cited 1 March 2022. https://projectsportal.afdb.org/dataportal/VProject/show/P-CV-FE0-001 and Nordman, E., Barrenger, A., Crawford, J., McLaughlin, J. & Wilcox, C. 2019. *Options for achieving Cape Verde's 100% renewable electricity goal: A review*. Island Studies Journal, 14(1): 41–58. https://doi.org/10.24043/isj.73
[5] ELEQTRA. 2021. Cabeolica Wind – Cape Verde. In: *ELEQTRA*. Cited 1 March 2022. https://eleqtra.com/projects/cabeolica-wind
[6] Nordman, E., Barrenger, A., Crawford, J., McLaughlin, J. & Wilcox, C. 2019. *Options for achieving Cape Verde's 100% renewable electricity goal: A review*. Island Studies Journal, 14(1): 41–58. https://doi.org/10.24043/isj.73
[7] ITA. 2021. Cabo Verde – Country commercial guide. In: *International Trade Administration*. Cited 1 March 2022. www.trade.gov/country-commercial-guides/cabo-verde-renewable-energy

3.3.3 BIOENERGY

Bioenergy is a form of renewable energy that is derived from biomass, such as wood processing and forestry residues, agricultural residues and organic waste. It is a versatile renewable energy source because it can be used to produce fuels, heat or electricity using a wide variety of different feedstocks and technologies. An overview of the bioenergy conversion routes is presented in **Figure 18**.

► FIGURE 18

Bioenergy conversion routes and final uses



Source: Authors' own elaboration.

Liquid biofuels, such as straight vegetable oil, ethanol and biodiesel can substitute fossil-based fuels in the transportation sector, while biomass can also be utilized as feedstock to generate electricity and heat through gasification, pyrolysis, anaerobic digestion or combustion (EERE, 2021e). Lastly, solid biofuels, such as pellets and briquettes, can be an effective solution to provide energy in several applications. They are generated from biomass through various processing steps, which include drying, grinding and densifying (i.e. pelletizing and briquetting), where the physical and chemical properties of the feedstock (i.e. particle size, moisture content) are enhanced. Additionally, densification results in an increased energy density of the fuel and thus it is possible to overcome handling difficulties, allowing for efficient and economic long-distance transport and storage (NRCAN, 2015).

- **Solid biofuels**

  Biomass pellets and briquettes are two major solid biofuels that can be used as substitutes to fossil fuels and the traditional use of fuelwood and charcoal. Due to their low moisture content and high energy density, these types of biofuels display a significantly high combustion efficiency. Pellets, which are made by compressing small particles of solid biomass, have a cylindrical shape and are manufactured in a large range of sizes, with their diameter typically varying from 6 mm to 25 mm and their length from 3 mm to 50 mm (Zafar, 2020). On the other hand, biomass briquettes are produced in different shapes (i.e. hexagon, cylinder), with larger diameters within the range of 50 mm to 90 mm and lengths ranging from 60 mm to 150 mm (Nielsen, 2021). A wide variety of feedstocks can be utilized, including forestry residues, animal waste, wood and agricultural waste, such as corn and cotton stalk, rice and coffee husks. Despite using the same type of feedstock, there are different requirements that have to be met regarding the raw materials (Kofman, 2007).

In a pelletizing installation, pre-processing of the feed is mandatory as low moisture content (i.e. less than 10 percent) and uniformity in particle size is vital to the successful production of high-quality pellets. On the other hand, a briquetting facility can handle a larger range of moisture in the feed of up to 20 percent, while not requiring any additional processing, thus resulting in lower investments and operating costs. However, pellets display some significant advantages, as they are easier to store and transport due to their higher bulk density (Nielsen, 2021). A typical overview of a pelletizing process is shown in Figure 19.

► **FIGURE 19**

Overview of pelletizing process

Source: Adapted from GEMCO Energy. 2021. Complete wood pellet production line for making quality biomass pellets. In: *GEMCO Energy*. Cited 31 January 2022. http://pellet.press/news/pelletizing-process.html

In the fisheries value chain, as well as in a variety of other applications, wood and charcoal are utilized to generate thermal energy. However, their extensive use and production can lead to deforestation and depletion of natural resources. In order to combat this issue, it is possible to produce biomass charcoal briquettes from several types of agricultural waste, as seen in Figure 20. This alternative presents several advantages: it is cost-effective and utilizes a potential that would otherwise be wasted. Sustainably sourced wood is also a suitable feedstock option for charcoal production and it can also be used directly to generate heat (Sugumaran and Seshadri, 2010). Sustainably sourced wood comes from sustainably managed forests, which minimize the impact of logging on the forest growth and, as a result, local resources, landscapes and ecosystems remain intact. It should be noted that wood processing residues and forestry residues, such as wood scraps, chips and sawdust, are also viable feedstock for thermal energy generation.

► **FIGURE 20**

Biomass charcoal briquettes production process

Source: KMEC. 2021. Charcoal briquette machine turns waste into energy. In: *KMEC Engineering.* Cited 31 January 2022. http://www.woodbriquetteplant.com/news/153.html

- **Factors affecting system output**

  The quality and burning efficiency of solid biofuels (i.e. pellets and briquettes) is mostly dependent on the properties of the feedstock. These include the type of biomass that is used, the moisture and ash content and the particle size. Additionally, parameters related to the manufacturing process, such as operating conditions and type of equipment, affect the final product.

  High moisture content (i.e. more than 15 percent of the gross weight) greatly reduces the calorific value of the solid biofuel, while ash content should be less than 1 percent to ensure a high-quality product. Moreover, high ash content can also have negative impacts on the equipment. In the case of biomass charcoal briquettes, volatile matter, which includes liquid and tarry residues that remain after carbonization, is another factor that has to be taken into account. High temperatures (i.e. more than 500 °C) and retention times during the carbonization process lead to a reduction in volatile matter. A high percentage of volatiles makes the charcoal briquettes easy to ignite and produces a lot of smoke, while a lower percentage means that the charcoal is harder to light but burns more cleanly (FAO, 1987; Garcia-Maraver and Carpio, 2015; Shukla and Vyas, 2015).

- **Siting and area requirements**

  A variety of parameters have to be considered for the siting of a bioenergy installation, in order to mitigate social and environmental impacts and ensure financial feasibility. The current uses, availability, types and spatial distribution of biomass resources are vital factors that affect the potential of a location and need to be taken into account. The collection, storage, processing and transport of feedstocks impose constraints on the economic viability of a bioenergy installation (Woo *et al.*, 2018). Choosing a location in the proximity of the currently available biomass and the consumption site of the final products can significantly reduce costs. The installation of a bioenergy plant has to comply with the regional and national legal requirements, while also avoiding competition with other land uses (Roman-Figueroa, Herrera and Paneque, 2019).

- **Global potential and installed capacity**

The availability of biomass for energy production, and therefore bioenergy potential, is directly related to the availability and quality of land used for agricultural and forestry production, food and feed demands, type of biomass used for energy generation and finally, energy conversion technologies applied. There are a number of published scientific papers focusing on current and future global bioenergy potentials which often vary considerably, from 50 EJ to 1 500 EJ per year, due to the different approaches and methods used. Even when sustainability aspects are considered, the ranges are rather large: from 60 EJ to 270 EJ per year (Dias *et al.*, 2021). A recently published paper, *Global potential assessment of available land for bioenergy projects in 2050 within food security limits* (Dias *et al.*, 2021), examines several scenarios for bioenergy potential based on availability of land and taking into consideration projections of population growth, projected food patterns and energy needs, while prioritising food security and environmental protection. According to this paper, under a pessimistic scenario, in 2050 biomass could contribute at least 5 percent of the global energy matrix, while the optimistic scenario would be that its contribution could reach as much as 17.7 percent of the projected 858 EJ energy consumed globally.

The global primary energy demand in 2019 was 603 EJ, of which 56 EJ, i.e. 9.2 percent, was of biomass origins (IEA, 2020). It should also be noted that a large portion of this was traditional biomass and that the main source of all bioenergy generated was woody biomass originating from forests. Over the past few decades, the use of modern bioenergy for heating, electricity generation and transportation has grown. In 2018, global pellet production surpassed 55 million tonnes (Bioenergy Europe, 2019) and the installed capacity of biomass-based power generation was more than 127 GW in 2020 (IRENA, 2021a). In both cases, Asia, Europe and North America are the largest producers and consumers of modern bioenergy. Table 8 shows wood pellet production in 2018 and the installed capacities of biomass-based power plants in 2020 per region.

► **TABLE 8**

Bioenergy production per region in 2018 and 2020

REGION	PELLET PRODUCTION IN 2018 (million tonnes)	INSTALLED BIOMASS POWER GENERATION CAPACITY IN 2020 (MW)
Asia	23.8	43 013
Europe	20.1	42 341
North America	10.9	15 406
South America	0.55	17 755
Eurasia	N/A	2 715
Africa	0.20	1 747
Oceania	0.20	1 077
Near East	N/A	105
Central America and Caribbean	N/A	3 043

Source: Bioenergy Europe. 2019. *Bioenergy Europe statistical report. Report pellet.* Brussels, Bioenergy Europe. https://epc.bioenergyeurope.org/wp-content/uploads/2020/02/SR19_Pellet_final-web-1.pdf and IRENA. 2021a. *Renewable capacity statistics 2021.* Abu Dhabi, IRENA. 300 pp.

► **BOX 3**

Bioenergy case study: Egypt

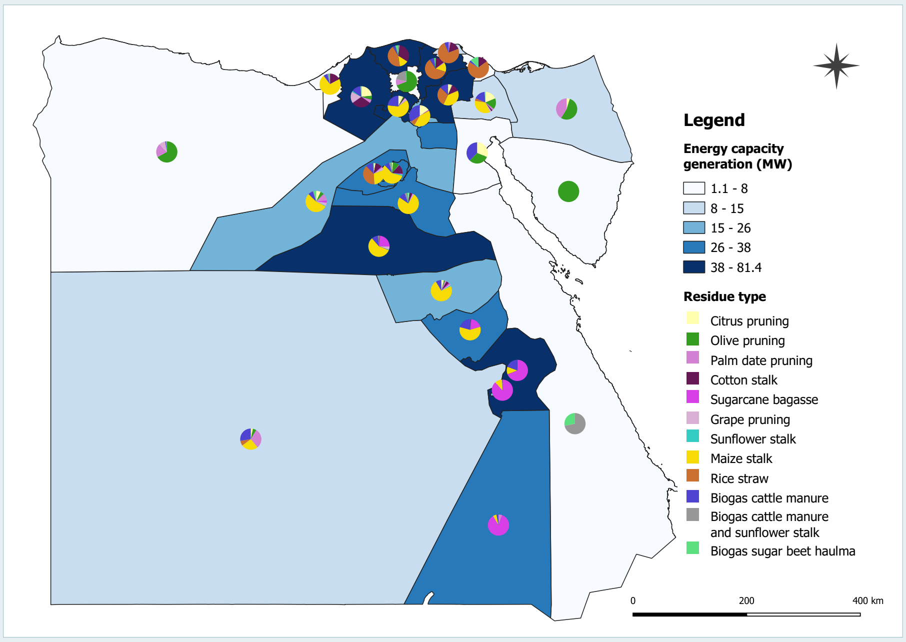
Despite its high renewable energy potential, Egypt still relies heavily on fossil fuels, which constituted more than 95 percent of the country's total final energy consumption in 2018. The installed capacity of renewables in 2020 was 5.9 GW, of which 2.8 GW was hydropower, 1.6 GW was solar and 1.4 GW was wind powerplants. Bioenergy use for electricity generation remains limited with only 79 MW.[1]

Even though currently there is limited development of the bioenergy sector in the country, crop and livestock residues in Egypt offer significant potential for bioenergy generation according to the Bioenergy and Food Security (BEFS) assessment conducted by FAO.[2] At a national level, approximately 5 million tonnes of crop residues are available annually for bioenergy production without jeopardizing environmental sustainability and food security. Maize stalks, rice straw, sugar cane bagasse and cotton stalk are the country's most common residue types, each with an availability of more than 500 000 tonnes per year. Additionally, approximately 777 000 tonnes of pruning from citrus fruit, olive, grape and palm date production are potentially available per year, adding to the bioenergy potential. Similarly, livestock residues can be utilized for energy generation, as it was estimated that 14 million tonnes of cattle manure is available on an annual basis.

The BEFS analysis of Egypt estimated that if all the available biomass were accessible and dedicated to electricity generation with CHP technologies (i.e. both CHP based on biogas and on direct combustion), then it would be possible to supply 772 MW, which could cover approximately 7 percent of the country's renewable energy capacity target. Utilizing this potential could supply electricity to 2.2 million households and avoid 2.9 million tonnes CO_2-equivalent/year. The first **Figure** shows the geographical distribution of the potential electricity generation capacity of CHP plants based on biogas and direct combustion. As seen in the legend of the map, light blue areas have a lower potential (i.e. less than 15 MW), while darker colours are indicative of a higher electricity generation potential, attaining 81 MW. The feedstocks with the highest potential for energy generation in Egypt are rice straw in the north, maize stalk in the middle and sugar cane bagasse in the south of the country, all through direct combustion.

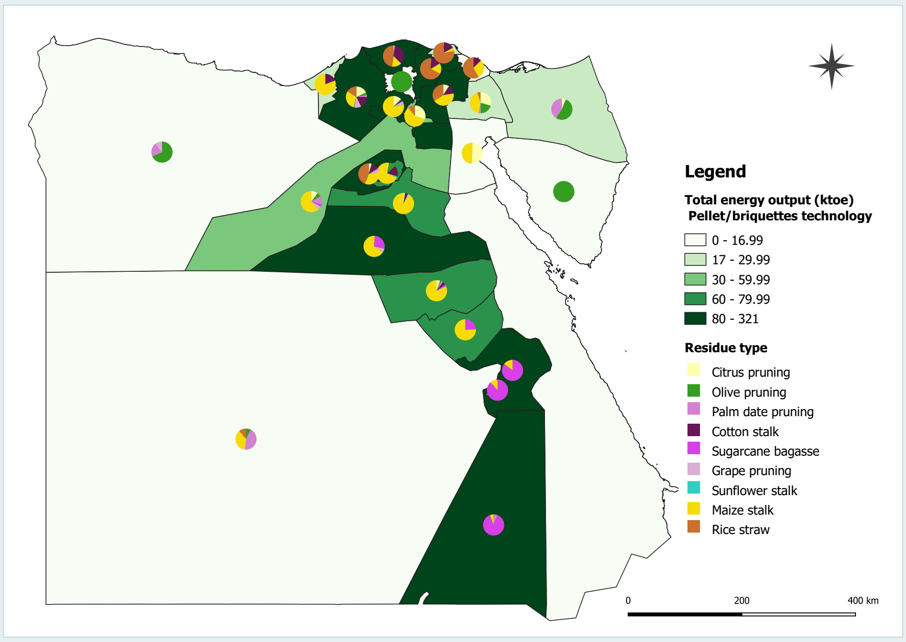
(Cont.)

Geographical distribution of total potential electricity generation capacity using combined heat and power technologies in Egypt



Source: FAO. 2017. *BEFS Assessment for Egypt: Sustainable bioenergy options from crop and livestock residues*. Environment and Natural Resources Working Paper No. 66. Rome, FAO.

Geographic distribution of total potential energy output using briquette/pellet technologies in Egypt



Source: FAO. 2017. *BEFS Assessment for Egypt: Sustainable bioenergy options from crop and livestock residues*. Environment and Natural Resources Working Paper 66. Rome, FAO.

(Cont.)

Similarly, in the case where all available crop residues are converted to briquettes or pellets, it would be possible to achieve a combined potential energy output of 1 878 ktoe/year, supplying energy to more than 1.6 million households and avoiding 3.6 million tonnes of CO_2-equivalent/year.[3] As seen in the second Figure, areas with a lighter green colour have lower potential outputs ranging from 1 ktoe to 30 ktoe, while the darker areas display higher potentials for energy outputs from briquette/pellets technologies, up to 321 ktoe.

According to the *2035 Integrated Sustainable Energy Strategy*, the government of Egypt aims to increase the share of renewable electricity in the energy mix to 20 percent by 2022 and to 42 percent by 2035. It is expected that the majority of these targets will be achieved through the establishment of solar, wind and hydropower plants.[4] There are several policies to support the successful integration of renewables. The Egypt Renewable Energy Law (Decree No 203/2014) was adopted in 2014 to encourage private sector investments in renewable electricity generation, by introducing feed-in tariff, competitive bids as part of supporting premium systems, and independent power production through third party access.[5] The Egypt renewable energy tax incentives (Presidential Decree No 17/2015) aims to increase the investments by reducing sales tax from 10 percent to 5 percent, while also setting customs duties on equipment used for production at 2 percent.[6]

Notes

[1] IRENA. 2021d. Energy Profile Egypt. In: *IRENA*. Cited 31 January 2022. www.irena.org/IRENADocuments/Statistical_Profiles/Africa/Egypt_Africa_RE_SP.pdf

[2] FAO. 2017. *BEFS Assessment for Egypt: Sustainable bioenergy options from crop and livestock residues*. Environment and Natural Resources Working Paper No. 66. Rome. https://www.fao.org/3/i6684e/i6684e.pdf

[3] FAO. 2017. *BEFS Assessment for Egypt: Sustainable bioenergy options from crop and livestock residues*. Environment and Natural Resources Working Paper No. 66. Rome. https://www.fao.org/3/i6684e/i6684e.pdf

[4] ITA (International Trade Administration). 2020. Egypt – Country commercial guide. In: *International Trade Administration*. Cited 1 March 2022. www.trade.gov/country-commercial-guides/egyptrenewable-energy

[5] IEA. 2016a. Egypt Renewable Energy Law (Decree No 203/2014) In: *IEA*. Cited 1 March 2022. www.iea.org/policies/6104-egypt-renewable-energy-law-decree-no-2032014?country=Egypt&qs=egy&topic=Renewable Energy

[6] IEA. 2016b. Egypt Renewable Energy Tax Incentives (Presidential Decree No 17/2015). In: *IEA*. Cited 1 March 2022. www.iea.org/policies/6105-egypt-renewable-energy-tax-incentives-presidentialdecree-no-172015?country=Egypt&qs=egy&topic=Renewable Energy

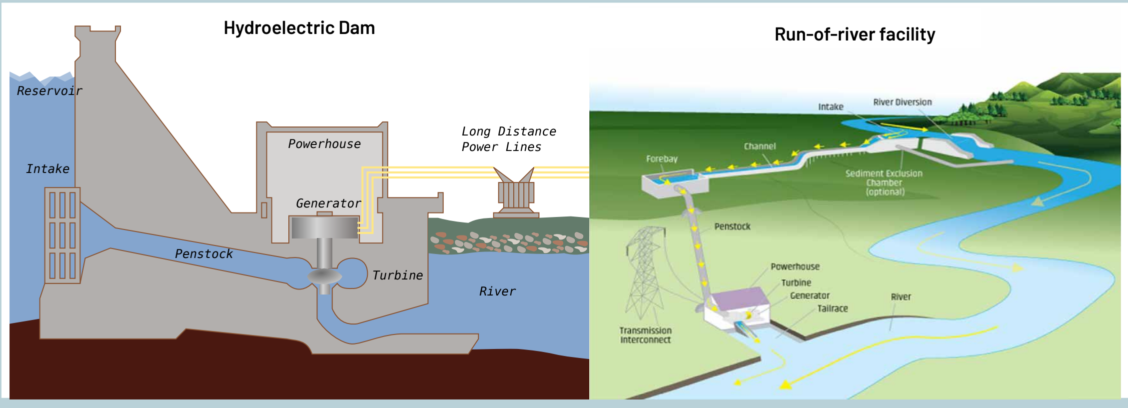
3.3.4 HYDROELECTRIC ENERGY

Hydroelectric energy, also called hydropower, is a form of renewable energy that can be harnessed from the power of water in motion. It is a reliable and low-cost source of electricity and is responsible for approximately 60 percent of the overall renewable electricity generation on a global scale (IHA, 2021b). In a hydropower installation, the energy of the flowing water is converted to mechanical energy using a hydraulic turbine. This energy is then used to produce electricity through a hydroelectric generator (USGS, 2021).

The most common type of hydropower plant is the impoundment facility that uses a dam to store river water in a reservoir. Water can then be released through a penstock in order to produce electricity based on demand. The second type of installation is called diversion or run-of-river. This type of facility channels a portion of the river through a canal or penstock and thus a dam may not be required (EERE, 2021f). The typical efficiency of a modern hydropower plant is approximately 85 percent to 95 percent, with an average lifespan ranging from 80 years to 100 years (Eurelectric and VGB, 2018). A simple illustration of an impoundment and a run-of-river facility is provided in Figure 21.

► FIGURE 21

Impoundment and run-of-river hydropower installations



Source: Adapted from EERE. 2021f. Types of hydropower plants. In: *EERE*. Washington, DC, US Department of Energy. Cited 31 January 2022. www.energy.gov/eere/water/types-hydropower-plants. www.energy.gov/eere/forge/geothermal-basics and TVA. 2000. Hydroelectric dam.svg. In: *Wikimedia Commons*. Cited 1 February 2022. https://commons.wikimedia.org/wiki/File:Hydroelectric_dam.svg

Hydropower installations can either be connected to the grid or operate autonomously. Power plants with an installed capacity greater than 10 MW are defined as large scale, while a capacity of between 0.01 MW and 10 MW is the generally accepted norm for small hydropower plants (IHA, 2017). Large-scale plants usually involve dams or reservoirs (i.e. impoundment facilities), while small hydropower installations are typically run-of-river facilities. Micro-scale installations, with a maximum installed capacity of 100 kW, can be used to power households or small communities and generally provide a very effective solution for decentralized electricity generation in remote areas (Energypedia, 2014).

- **Factors affecting system output**

  The electricity generation of a hydropower installation is dependent on several location characteristics. First, the supply of water greatly affects the potential production, thus climate factors such as precipitation, humidity and temperature have to be taken into account. The degree of slope is another vital parameter; a steeper slope can yield higher electricity outputs for the system. The quality of water is also of significance as silt free water will not damage the equipment. Second, geological stability is important to ensure sturdy construction for the dam in the case of impoundment facilities (IHA, 2021a).

- **Siting and area requirements**

  The siting of a hydropower installation can significantly affect the electricity outputs of the system. A hydroelectric facility has to be located along the path of a river and preferably at a place where the stream narrows, allowing for higher flow and easier collection or diversion of water. Different considerations have to be made for large-scale facilities that require a dam, and smaller installations that are run-of-river.

  In large-scale installations, in order to mitigate negative terrestrial impacts, the construction of the power plant must take place in a manner that prevents sedimentation and erosion risks up and down stream of the site. Moreover, integrating other water uses (e.g. irrigation) must be considered to improve sustainability, while also avoiding conflicts with existing water-related projects (IHA, 2021a; UNIDO, 2019). Lastly, the flow of water should be sufficient to accommodate evaporation losses in the dam and thus ensure that no water shortages occur, as they can be damaging to the turbines of the system. For small-scale hydropower installations, optimal locations include steep rivers that flow continuously throughout the year. In order to achieve good performance and high electricity production, the flow should be more than 20 L/s, while the difference in height between the intake and the turbine should be at least 1 m to 2 m (Energypedia, 2021).

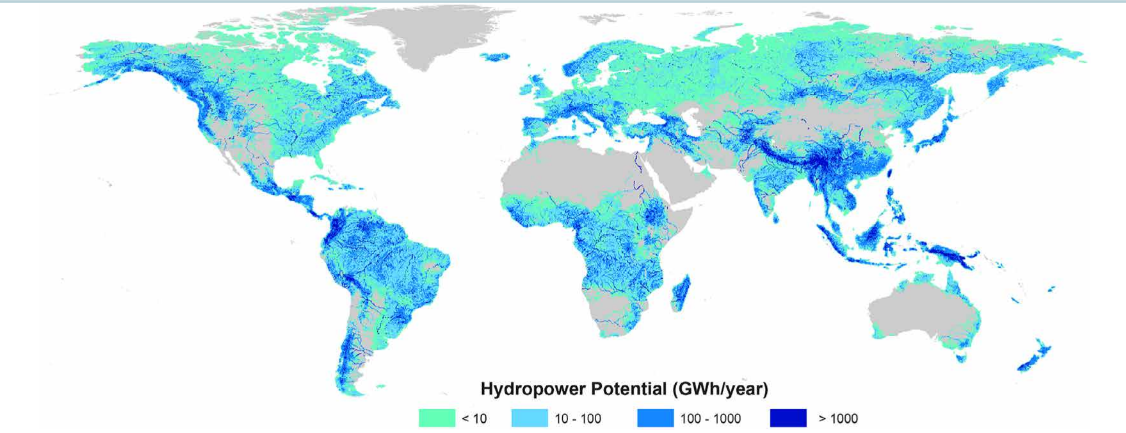
Area requirements for hydropower generation can vary greatly between specific facilities and countries, due to differences in the characteristics of each installation. On average, the land occupation of hydroelectric stations in the United States of America is estimated to be approximately 0.01 ha to generate 1 MWh of electricity (Nussey, 2020), while in Norway it was calculated at 0.0027 ha per MWh (Dorber, May and Verones, 2018).

- **Global potential and installed capacity**

  The geographic distribution of the hydropower potential is presented in **Figure 22**. The areas marked in green on the map display the potential output of less than 10 GWh per year. The darker blue colours are indicative of a significant hydropower potential of more than 1 000 GWh per year. Large areas of North and South America, Europe and Africa show high potentials but the potential in Asia is by far the highest, representing nearly 50 percent of the overall global potential.

► **FIGURE 22**

Global hydropower potential



Source: Conforms to UN. 2023. Map No. 4170, Rev. 19. Hoes, O., Meijer, L.J.J., van der Ent, R.J. & van de Giesen, N.C. 2017. *Systematic high-resolution assessment of global hydropower potential*. PLOS ONE, 12(2). https://doi.org/10.1371/journal.pone.0171844

In 2020 the installed capacity of hydropower globally was more than 1 200 GW, out of which approximately 40 percent is in Asia. As presented in **Table 9**, in 2020 Europe had nearly 195 GW of hydropower installed capacity, followed by North America and South America, each with almost 178 GW. The hydropower capacities in Central America and the Caribbean were nearly 8.3 GW.

► **TABLE 9**

Hydropower installed capacity per region in 2020

REGION	INSTALLED CAPACITY IN 2020 (MW)
Asia	501 211
Europe	194 129
South America	177 978
North America	177 787
Eurasia	88 354
Africa	34 113
Near East	16 223
Oceania	13 643
Central America and Caribbean	8 254

Source: IRENA. 2021a. *Renewable capacity statistics 2021*. Abu Dhabi, IRENA. 300 pp.

► **BOX 4**

Hydroelectric energy case study: Mozambique

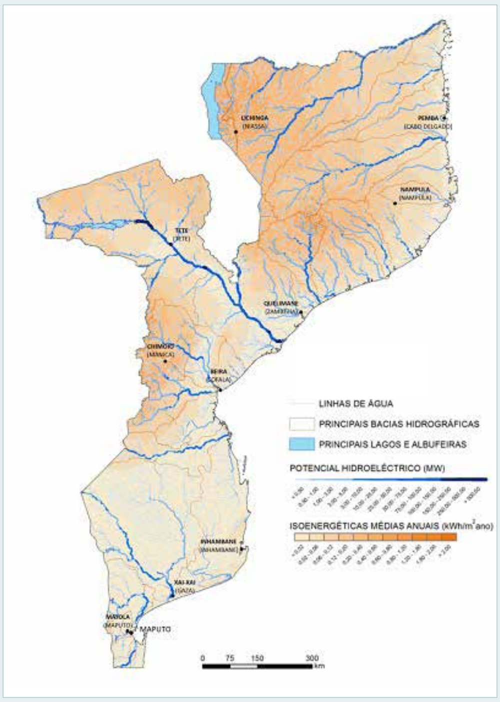
Mozambique is rich in renewable energy potential and in 2018 renewable energy accounted for 66 percent of the total final energy consumption. Electricity generation in the country is largely based on hydropower (2.2 GW), followed by fossil-based power plants (600 MW). Electricity is also supplied to a smaller extent by solar (95 MW) and bioenergy (14 MW).[1] The geographical distribution of the hydropower potential in Mozambique is presented in the **Figure**. The light blue areas on the map display the lowest hydropower potential, with less than 10 MW of the installed capacity, while the darker blue areas are indicative of improved conditions, where the installed capacity can potentially achieve 500 MW or more.

Mozambique's hydropower potential is estimated to be among the highest in sub-Saharan Africa at approximately 12.5 GW, with more than 80 percent of that located in the Zambezi Valley. The Renewable Energy Atlas identified 1 446 potential sites for hydropower installations in the country. More than 400 of those are suitable to power minigrids and ensure access to electricity in remote locations, reaching an overall potential of 2.1 GW (AfDB, 2017).[2]

Currently there are several operating hydropower stations in Mozambique, assuming an overall installed capacity of approximately 2.2 GW (IHA, 2020).[3] There are 24 pico-hydropower installations (overall approximately 100 kW), while 19 microscale plants account for 450 kW. Additionally, there are six large-scale installations in the country. The 2 075 MW Cahora Bassa plant is by far the largest. The government aims to further increase hydropower capacity, introducing two large-scale projects in the near future, which include the expansion of the Cahora Bassa plant, with an addition of 1 245 MW, and the development of the Mphanda Nkuwa Dam, with an installed capacity of 1 500 MW (Mokveld and Eije, 2018).[4] Smaller hydropower installations are also part of the plans to develop the sector, with the Majaua (530 kW), Rotanda (620 kW), Muoha (100 kW), Senbezeia (62 kW) and Chiurairue (23.1 kW) installations currently under development (Klunne, 2021).[5]

(Cont.)

Hydroelectric potential in Mozambique



Source: Conforms to UN. Map No. 3706, Rev. 7, July 2020. Adapted from FUNAE. 2021. ATLAS Energias Renovaveis de Mocambique. In: *FUNAE – Fundo de Energia*. Cited 28 April 2022. https://funae.co.mz/recursos-hidricos/

Several policies have been put in place to support the integration of renewables and the development of the hydropower and other sectors. The Energy Reform and Access Project (2003–2011) was a World Bank project that aimed to accelerate access to electricity by introducing solar PV systems and microhydro installations (IEA, 2017).[6] Building on this initiative, the Poverty Reduction Action Plan 2011–2014 included similar measures (IEA, 2015a).[7] Lastly, there is policy support in the form of renewable energy feed-in tariffs, ensuring power purchase agreements for small hydropower plants up to 10 MW capacity (IHA, 2020).[8]

Notes

[1] IRENA. 2021e. Mozambique – Energy profile. In: *IRENA*. Cited 31 January 2022. www.irena.org/IRENADocuments/Statistical_Profiles/Africa/Mozambique_Africa_RE_SP.pdf
[2] AfDB (African Development Bank). 2017. Green Mini Grid Market Development Programme: Mozambique. In: *AfDB*. Cited 1 March 2022. www.aler-renovaveis.org/contents/lerpublication/afdb_2017_abr_mini-grid-market-opportunity-assessment-mozambique.pdf
[3] IHA. 2020. Country profile – Mozambique. In: *IHA*. Cited 1 March 2022. www.hydropower.org/countryprofiles/mozambique
[4] Mokveld, K. & Eije, S. von. 2018. *Final energy report Mozambique*. Netherlands Enterprise Agency: 1–43.
[5] Klunne, W.J. 2021. African hydropower database – Mozambique. In: *Hydro4Africa*. Cited 28 April 2022. https://hydro4africa.net/HP_database/country.php?country=Mozambique&tab=overview
[6] IEA. 2017. Energy Reform and Access Project (2003–2011). In: *IEA*. Cited 1 March 2022. www.iea.org/policies/5868-energy-reform-and-access-project-2003-2011?country=Mozambique&qs=moza&technology=Hydropower %28excl. pumped hydro%29&topic=Renewable Energy
[7] IEA. 2015a. Poverty Reduction Action Plan 2011–2014 (PARP). In: *IEA*. Cited 1 March 2022. www.iea.org/policies/5869-poverty-reduction-action-plan-2011-2014-parp?country=Mozambique&qs=moz&technology=Hydropower%28excl. pumped hydro%29&topic=Renewable Energy
[8] IHA. 2020. Country profile – Mozambique. In: *IHA*. Cited 1 March 2022. www.hydropower.org/countryprofiles/mozambique

3.3.5 GEOTHERMAL ENERGY

Geothermal energy is thermal energy derived from the subsurface of the Earth in the form of steam or hot water, which can be harnessed from reservoirs of varying temperatures and depths. Depending on their characteristics (i.e. depth, geofluid temperature), geothermal energy can be utilized for heating and cooling applications, or for electricity generation (IRENA, 2021f). The temperature of the geofluid is the main parameter for the classification of geothermal resources and the main categories are high (>150 °C), middle (100 °C to 150 °C) and low (30 °C to 100 °C) temperature reservoirs (ICGC, 2021). Due to the variety of geothermal resources, it is possible to generate electricity or heat, both on a large and a small scale depending on the application (NREL, 2021b).

- **Geothermal electricity**

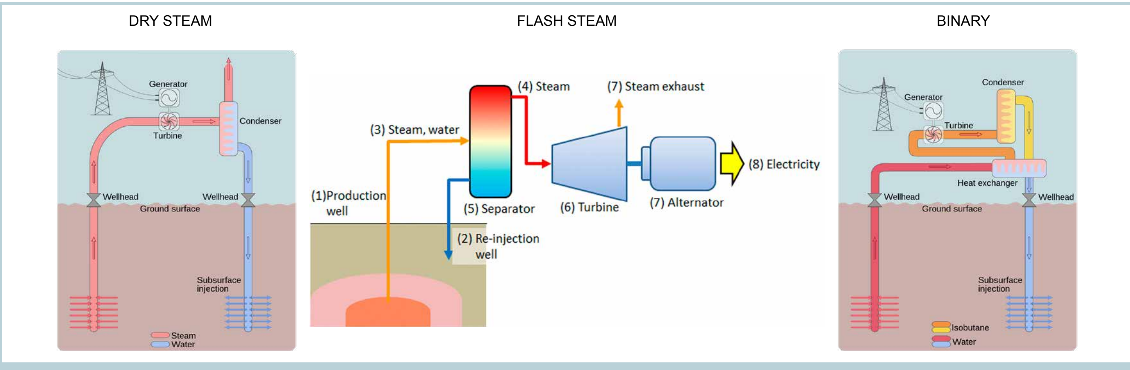
  Electricity generation from geothermal resources can occur both on a large and small scale, while also offering the possibility to cover the electricity demand in remote locations through microgrids. Geothermal power is reliable and it can provide continuous electricity to combat the variability of other renewable energy sources, such as wind and solar. The typical lifespan of a geothermal power plant is approximately 20 years to 30 years (GEA, 2016).

  There are three main types of geothermal power plants for the generation of electricity. In dry steam and flash steam power plants, steam passes through a turbine which drives a generator, thus electricity can be produced. Dry steam facilities require steam dominated reservoirs, while in flash steam plants, the feedstock can be a mixture of steam and water, which is then separated in a flash vessel. Despite their several advantages, these types of installations require high temperature reservoirs, and operate optimally at temperatures higher than 182 °C, resulting in significant location restrictions because such resources are not particularly common.

  However, in recent years the binary cycle technology has gained increased attention and has facilitated the efficient utilization of medium-temperature reservoirs for power generation (IRENA, 2021d). In a binary cycle plant, the geofluid is used to heat a secondary fluid (e.g. isobutane) with a much lower boiling point (EERE, 2021g). An overview of the difference between the three types of geothermal power plants is presented in Figure 23.

▶ **FIGURE 23**

Overview of the three different types of geothermal power plants



Source: Adapted from Abubakr, R. 2018. Geothermal binary system (alt version).svg. In: *Wikimedia Commons*. Cited 31 January 2022. https://commons.wikimedia.org/wiki/File:Geothermal_Binary_System_(alt_version).svg; Wikimedia Commons, 2012; Teken, G. 2014. Diagram vapor dominated geothermal inturperated version.svg. In: *Wikimedia Commons*. Cited 1 February 2022. https://commons.wikimedia.org/wiki/File:Diagram_VaporDominatedGeothermal_inturperated_version.svg

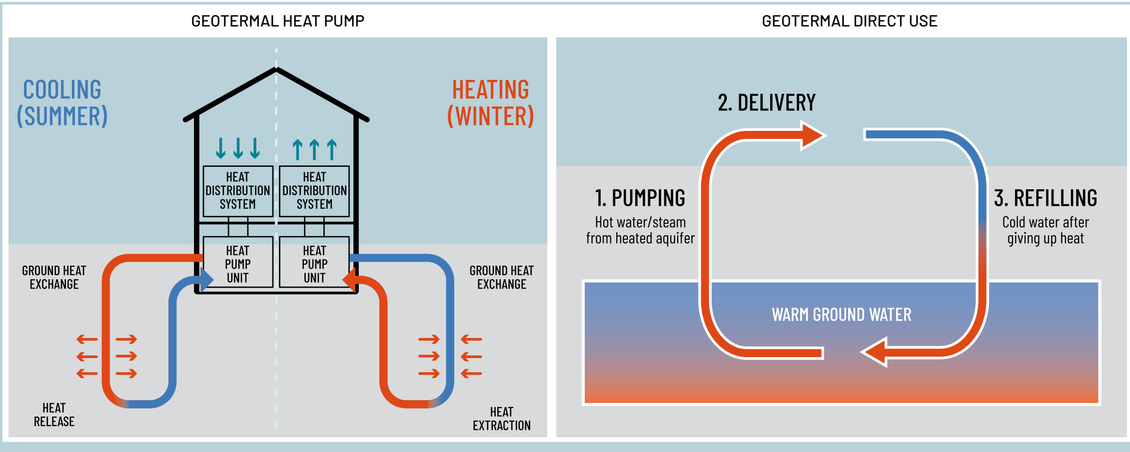
- **Geothermal heat**

  Low and medium temperature geothermal reservoirs are widely available and can be utilized for heating and cooling purposes. They can provide heat directly (i.e. from hot water in the reservoir) for applications on a residential, commercial or industrial scale, such as district and space heating, commercial greenhouses, aquaculture, food processing facilities and a variety of other applications. The direct use of geothermal energy offers many benefits because it is much less expensive than traditional fossil fuels, while also avoiding the emission of hazardous pollutants (EERE, 2004).

  Additionally, geothermal heat pumps can provide a sustainable and efficient solution for space heating and cooling, as well as water heating for both residential and commercial buildings (EERE, 2021g). A geothermal heat pump takes advantage of the constant temperature below the Earth's surface by exchanging heat with the Earth through a ground heat exchanger. A fluid is used to either absorb or relinquish heat within the ground and thus control the temperature of the indoor space. Heat pumps, with a typical lifespan of more than 20 years and a much greater efficiency than conventional heating or cooling systems (EERE, 2011), can support space heating and cooling needs in a vast variety of locations, as they are not limited by geography or geology (GEA, 2016). An overview of a heat pump and the direct use of geothermal heat is depicted in Figure 24.

FIGURE 24

Overview of geothermal heat utilization



Source: Adapted from EPA. 2021b. Geothermal heating and cooling technologies. In: *EPA. Washington, DC, US Environmental Protection Agency.* Cited 31 January 2022. www.epa.gov/rhc/geothermal-heating-and-cooling-technologies and Jeon, J.S., Lee, S.R. & Minjun, K. 2018. A modified mathematical model for spiral coil-type horizontal ground heat exchangers. Energy, 152. https://doi.org/10.1016/j.energy.2018.04.007

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- **Factors affecting system output**

The output of a geothermal system greatly depends on the characteristics and availability of the geofluid. Higher temperatures are indicative of an increased potential to generate electricity and heat, while a high mass flow can lead to improved performance of the power station. However, the corrosive nature of the geofluid can negatively impact the performance of the system because more frequent maintenance will be required, resulting in higher costs. In the case of binary plants, the working fluid that has been selected will also affect the feasibility and outputs of the facility (Domanski *et al.*, 2015). Lastly, the condition of the soil can affect the performance of the heat pump system. Moist soil with small temperature variations can ensure an optimal result. The type of soil also affects the outputs, with saturated sand being preferred (Alvarez, 2015).

- **Siting and area requirements**

Geothermal energy is a location specific energy source because reservoirs are found only in specific areas. High temperature resources, which are required for electricity generation, are more scarce and are located near the boundaries of the Earth's tectonic plates. Therefore, the siting of geothermal power plants requires careful planning and identification of reservoir location. Apart from determining a site with an available geothermal resource, various other factors must be considered. Regional and local geology, steam availability, historic seismicity and proximity to transmission lines should be a priority when establishing a power plant. Additionally, potential conflicts with other land uses have to be examined (Maclellan, 2011). In the case of heating and cooling applications (i.e. direct use or heat pumps), location restrictions are diminished because lower temperature reservoirs are more common (Gonzalez, 2020). Heat pumps that utilize the constant temperature of the earth show significant flexibility with siting because they are not bound by geography and can be installed practically anywhere. For the direct use of geothermal resources for heating purposes, reservoirs with hot water have to be identified. While they are readily available, identifying the appropriate location is more complex when compared to the case of heat pumps.

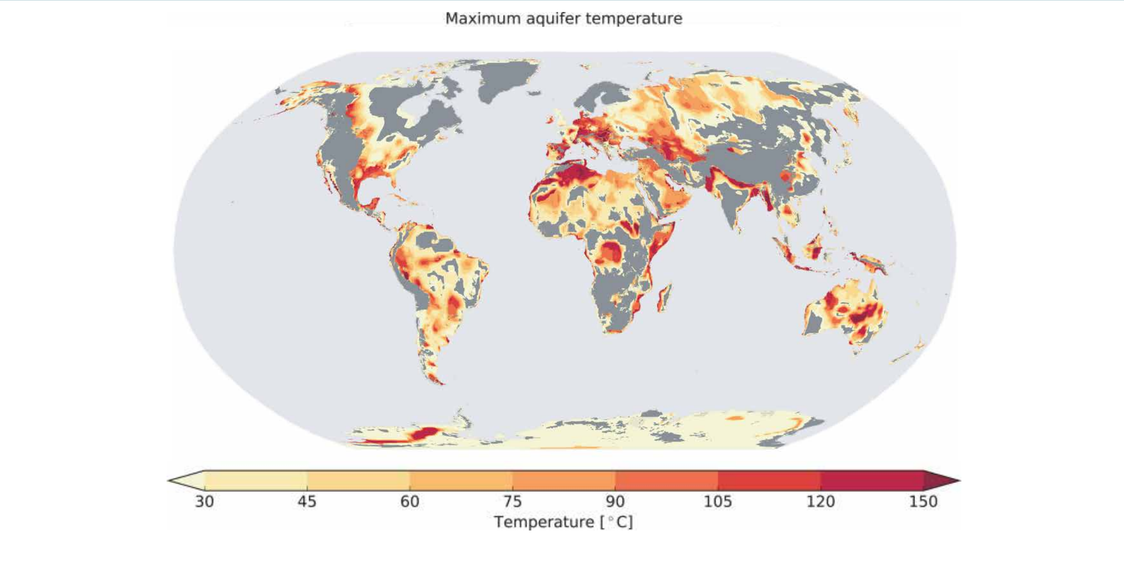
- **Global potential and installed capacity**

  Electricity generation from geothermal resources is restricted to high temperature reservoirs which are scarce and found only at specific locations. These types of installations are typically large-scale and feature high installation and operating costs. Geothermal electricity generation presents a global potential of approximately 190 GW (IRENA, 2021a).

  The energy potential of geothermal resources for direct heat utilization is correlated with the temperature of the resource, which is presented in the map in Figure 25. The areas marked in yellow and orange indicate a resource temperature lower than 75 °C, while in the red coloured areas the resource temperatures attain 150 °C.

► FIGURE 25

Global potential for direct use of geothermal energy for heating purposes



Source: Conforms to UN. 2023. Map No. 4170, Rev. 19. Limberger, J., Boxem, T., Pluymaekers, M., Bruhn, D., Manzella, A., Calcagno, P., Beekman, F. *et al.* 2018. *Geothermal energy in deep aquifers: A global assessment of the resource base for direct heat utilization.* Renewable and Sustainable Energy Reviews, 82: 961–975. https://doi.org/10.1016/j.rser.2017.09.084

In 2019, the global installed thermal capacity for the direct use of geothermal energy reached approximately 107 GW_{th} and Asia was responsible for nearly 46 percent of the total (see Table 10). Europe, North America and the Commonwealth of Independent States followed with nearly 32.5 GW, 23 GW and 2 GW of installed thermal capacity respectively, while the remaining regions all displayed capacities of less than 1 GW. The global installed capacity for geothermal power (i.e. electricity generation) reached more than 14 GW in 2020.

► **TABLE 10**

Geothermal direct use installed capacity per region in 2019

REGION	INSTALLED CAPACITY IN 2019 (MW_{TH})
Asia	49 079
Europe	32 386
North America	22 700
Commonwealth of Independent States	2 121
South America	621
Oceania	613
Africa	198
Central America and the Caribbean	9

Source: Lund, J.W. & Toth, A.N. 2021. *Direct utilization of geothermal energy 2020 worldwide review. Geothermics, 90: 101915.* https://doi.org/10.1016/j.geothermics.2020.101915

► **BOX 5**

Geothermal energy case study: Indonesia

In Indonesia, renewable energy sources contributed 20.9 percent to the total final energy consumption in 2018. The overall capacity of renewables in the country was more than 10 GW in 2020, out of which 6.2 GW is in hydropower plants. Geothermal energy and bioenergy follow with approximately 2.1 GW and 1.9 GW, respectively. Wind and solar energy are currently less developed, both having capacities ranging from 150 MW to 170 MW (IRENA, 2021g).[1]

Indonesia's geothermal energy potential is estimated to be around 28 GW, accounting for 40 percent of the global potential (Richter, 2020).[2] Indonesia aims to supply 23 percent of the primary energy supply from renewables by 2025 and further increase that share to 31 percent by 2050. Geothermal energy will play an important role in achieving these targets (IRENA, 2017c).[3] In addition to the existing geothermal power plants (some of which are depicted in the **Figure**, the government plans to introduce 177 new geothermal projects, reaching an electricity generation capacity of 8 GW by 2030 (Richter, 2020).[4]

While the main focus in the country is currently on generating electricity from geothermal resources, several projects focused on the direct use of geothermal energy for heating are under development. The most common use of direct geothermal energy is for bathing and heating swimming pools. Additionally, there are several applications in agriculture, such as mushroom cultivation, palm sugar production, as well as coconut copra and cocoa drying. Direct use of geothermal energy also applies for aquaculture and space heating purposes (Surana, Atmojo and Subandriya, 2010).[5]

The growth of geothermal energy in Indonesia has been endorsed by several government policies and support measures, such as the Ceiling Price for Geothermal (Ministerial Regulation No. 17/2014), the New Geothermal Law (No. 21/2014) and the Geothermal Fund (Ministry of Finance Regulation No. 3/2012). Through the Purchase of Electricity from Geothermal Plants (Regulation No. 02/2011), the price of electricity from geothermal power plants has become fixed and non-negotiable (IEA, 2015b).[6]

(Cont.)

Location of major geothermal power plants in Indonesia

Source: Conforms to UN. 2023. Adapted from Map No. 4365 Rev. 1 United Nations, March 2012. Richter, A. 2020. Additional 5,880 MW of geothermal capacity planned for Indonesia. In: *ThinkGeoEnergy*. Cited 1 March 2022. www.thinkgeoenergy.com/additional-5880-mw-of-geothermal-capacity-planned-for-indonesia

Notes

[1] IRENA. 2021g. Ocean energy. In: *IRENA*. Cited 31 January 2022. www.irena.org/ocean
[2] Richter, A. 2020. Additional 5,880 MW of geothermal capacity planned for Indonesia. In: *ThinkGeoEnergy*. Cited 1 March 2022. www.thinkgeoenergy.com/additional-5880-mw-of-geothermal-capacityplanned-for-indonesia
[3] IRENA. 2017c. Electricity storage and renewables: Costs and markets to 2030. In: *IRENA*. Cited 31 January 2022. www.irena.org/publications/2017/oct/electricity-storage-and-renewables-costsand-markets
[4] Richter, A. 2020. Additional 5,880 MW of geothermal capacity planned for Indonesia. In: *ThinkGeoEnergy*. Cited 1 March 2022. www.thinkgeoenergy.com/additional-5880-mw-of-geothermal-capacityplanned-for-indonesia
[5] Surana, T., Atmojo, J.P. & Subandriya, A. 2010. *Development of geothermal energy direct use in Indonesia*. GHC Bulletin, 8: 11–15. www.oit.edu/docs/default-source/geoheat-center-documents/quarterly-bulletin/vol-29/29-2/29-2-art3.pdf?sfvrsn=4
[6] IEA. 2015b. Purchase of Electricity from Geothermal Plants (Regulation No. 02/2011). In: *IEA*. Cited 1 March 2022. www.iea.org/policies/5682-purchase-of-electricity-from-geothermal-plants-regulationno- 022011?country=Indonesia&qs=indo&technology=Geothermalelectricity%2CGeothermal&topic=Renewable Energy

3.3.6 MARINE ENERGY

Marine energy, also known as ocean energy, involves harnessing energy from the sea to generate electricity. There are several emerging marine energy technologies which display a lot of potential, but they are still at the developmental stage and are not yet commercially available (IRENA, 2021g).

- **Wave energy**
  The kinetic energy of waves can be captured and converted into useful work, which is then utilized for electricity generation, water desalination or water pumping purposes. Wave energy converters (WEC) can operate both close to the shoreline, as well as ion offshore waters, where the potential is increased. Several different types of WECs have been identified, including absorbers, attenuators, oscillation water columns, as well as overtopping and submerged pressure differential devices (EMEC, 2021; OpenEI, 2015).

- **Tidal energy**
  Tidal energy can be harnessed by converting the energy from tides into useful forms of power, i.e. mainly electricity, through two main methods. Tidal-range technologies use a structure called a barrage that is installed across the inlet of an ocean bay in order to harvest power between high and low tide. Tidal stream devices, similar to wind turbines, are usually placed on the sea floor where

the tidal flow is stronger. It is common to install concentrators around the blades to streamline the flow towards the rotor, thus increasing the power output of the system. Despite being a variable energy source, tidal energy shows a higher predictability compared to other renewables, such as wind or solar energy (EIA, 2020c; EMEC, 2021).

- **Thermal conversion energy**
  The ocean thermal gradient between warmer surface and cooler deep water can be exploited to produce electricity through a heat engine. During the operation of such a system, there are two main byproducts. Cold water can be used for air-conditioning and refrigeration purposes, while desalinated water is available for drinking or irrigation applications. Ocean thermal conversion energy is of great importance because it displays a much larger resource potential compared to the other ocean energy forms, while also being able to supply base-load power, due to its high availability and capacity factor (EIA, 2020d).

- **Salinity gradient energy**
  Salinity gradient energy is the energy derived from the difference in salt concentration between seawater and river water. Reverse electrodialysis and pressure retarded osmosis are two emerging technologies that rely on osmosis with membranes, but they are still in the development phase. In both processes, the salinity gradient difference is responsible for transporting ions, which results in electric potential that leads to electricity generation (IRENA, 2014).

- **Global potential and installed capacity**
  Marine energy technologies are still in the development phase and they are only available to a limited extent, as seen in Table 11. Asia and Europe are by far the most advanced regions in this regard, as they display installed capacities of 260 MW and 243 MW respectively. North America has only 20 MW of marine energy installations, with the remainder of the regions showing a lack of development.

▶ TABLE 11
Marine energy installed capacity per region in 2020

REGION	INSTALLED CAPACITY IN 2020 (MW)
Asia	260
Europe	243
North America	20
Eurasia	2
Oceania	1
South America	-
Africa	-
Near East	-
Central America and Caribbean	-

Source: IRENA. 2021a. *Renewable capacity statistics 2021.* Abu Dhabi, IRENA. 300 pp. https://www.irena.org/publications/2021/March/Renewable-Capacity-Statistics-2021

4. SPECIFIC RENEWABLE ENERGY INTERVENTIONS BY VALUE CHAIN STAGES

The previous chapters introduced the role of energy in small-scale fish value chains. They described how manual labour, conventional fuels and electricity are essential sources of energy that drive power lamps, refrigerators, dryers, boats and other relevant units to process, store and distribute the final product.

However, the energy sources mentioned earlier can also be substituted or complemented by RES. Solar PV, hydro, wind and biomass-based energy can generate useful energy such as electricity and power to drive motors used in boats and refrigerators. Moreover, other options such as geothermal energy and direct biofuel combustion can generate the heat needed for aquaculture, and drying for fish processing.

At the small scale, small production units prevail, which, linked to low capital investments and different technology limitations, yield significant percentages of losses and low-income levels for fish farmers (Akande & Diei-Ouadi, 2010; FAO, 2021a).

Therefore, interventions across small-scale fish value chains are essential to modernizing value chains, despite the fact that such interventions initially imply additional capital investments that might create a barrier for small-scale fishers and fish farmers. However, in the long term, these interventions can bring benefits to the families and communities of fishers and fish farmers. The benefits include:

- higher incomes from larger catches and optimal fish farming production;
- more extensive preservation time;
- better final product distribution, which overall implies fewer end product losses; and
- the interventions might reduce production costs, increase income and improve the working conditions of fishers and fish farmers.

This chapter presents different options for renewable energy interventions suitable for small-scale fisheries value chains. Most of the interventions proposed are based on the country profiles published by the FAO Fisheries Division (FAO, 2021d). These country profiles provide information on aquaculture, large-scale, small-scale, post-harvest uses and fishing markets. Also, they describe the limitations, barriers, trends and potential sector development areas, including where energy and technology improvements are needed. Moreover, the information on technology and equipment suitable for renewable energy intervention was collected from different scientific and market sources.

4.1 HOW CAN RENEWABLE ENERGIES INTERVENE IN A FISH VALUE CHAIN?

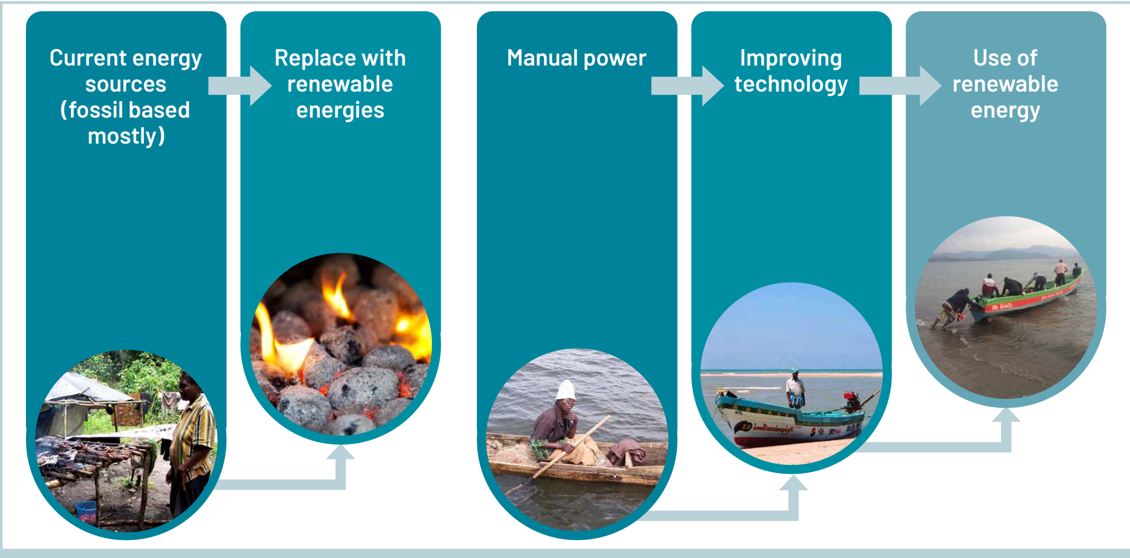
When considering the use of renewable energy in the fish value chain, the choice of optimal technology will depend on the final energy form needed in the specific part of the value chain, and the geoclimatic and infrastructure context at the location of application. As described in the previous section, in case of electricity and heat, renewable energy technologies can be an integrated part of production facilities that supply energy to the transmission and/or distribution grids, or they can operate as off-grid facilities that supply the energy into a minigrid, or directly to the final user.

In countries with well-developed energy transmission and distribution infrastructure, and policies that promote the use of renewable energy, on-grid solutions are commonly the most cost-effective way of using renewable energy technologies. In such cases, the level of renewable energy contribution to the country's energy mix depends on the natural potential of the specific renewable energy and the level of market development. However, in countries that face difficulties with security of energy supply, the deployment of renewable technologies that operate off-grid can increase energy access and security of supply and, thus provide numerous benefits for energy consumers.

The deployment of renewable energy in the fisheries value chain can be in the form of a direct substitution of the currently used energy source, or involve the modification or improvement of the currently used technology/appliances in a specific part of the value chain (see Figure 26).

▶ **FIGURE 26**

Directions in renewable energy interventions



Source: Authors' own elaboration.

Image sources: Colfer, C./CIFOR. 2017. Smoking fish at an encampment on the Ivindo River, Gabon, Africa. In: *Flickr.* Cited 28 April 2022. www.flickr.com/photos/cifor/36376964380/in/photostream; Kratochvil, P. n.d. Burning charcoal briquettes. *In: Public Domain Pictures.net*. Cited 28 April 2022. www.publicdomainpictures.net/en/view-image.php?image=24108&picture=burning-charcoal-briquettes; Calixto. 2017. Local fishing on Lake Victoria; a wonder for what to eat and how to survice. *In: Wikimedia Commons.* Cited 28 April 2022. https://commons.wikimedia.org/wiki/File:Local_Fishing_on_Lake_Victoria;_a_wonder_for_what_to_eat_and_how_to_survice.jpg; Kelleher, K./USAID. 2016. In: *Pixnio.* Cited: 28 April 2022. https://pixnio.com/sport/fishing-and-hunting/repaired-fishing-boat-armed-with-a-restored-motor-awaits-launching#img_info; Torqueedo. 2020. The fishermen take to the lake in the evening to catch omena, aka Lake Victoria sardines In: *Torqueedo.* Cited 28 April 2022. https://www.torqeedo.com/en/news-and-press/blog/blog-2020-8-26.htm

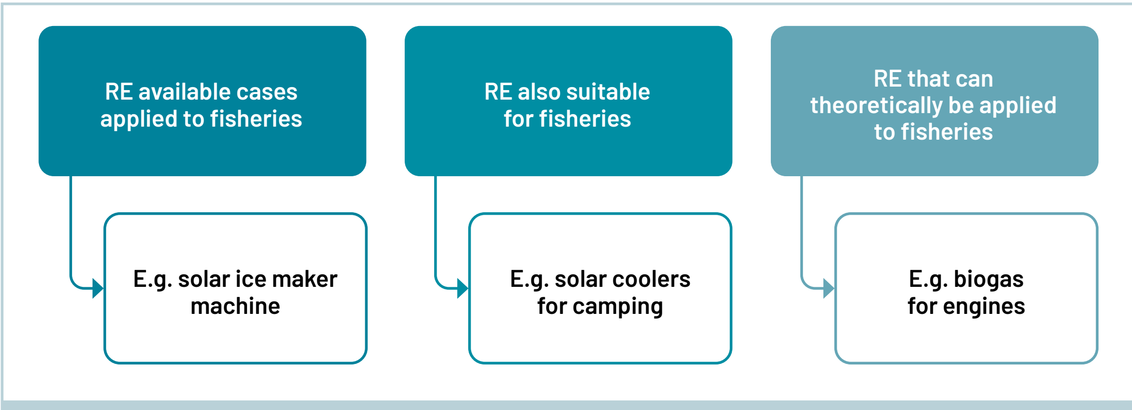
For example, fish farmers can substitute firewood or charcoal used for drying or smoking fish with briquettes produced from sustainably sourced woody or crop residues, without substantial changes to the drying/smoking technology in use. Furthermore, the organoleptic properties of the smoked fish are similar, while most negative environmental impacts are mitigated (Mindjimba *et al.*, 2019). Another such example is the installation of an off-grid rooftop PV plant or a micro-hydropower plant, which could substitute the use of diesel generators on a fish farm. If the farm requires continuous access to electricity, a full substitution of the diesel generator would also require the installation of a battery equipped rooftop PV or micro hydropower plant. As in the previous example, there is no need to change appliances used on the fish farm, while the substitution can result in improved energy security and lower production costs for the farm.

As mentioned earlier, the deployment of renewable energy can be part of the technological improvements in the value chain, which can result in added value to the final product or improved welfare of fish farmers. Examples of such improvements are: (i) the installation of an electrical engine with batteries on catch boats that are currently powered manually; (ii) the installation of heat-pumps or direct use of low-temperature geothermal wells for heating fish ponds and/or fish hatcheries in aquaculture; and (iii) the installation of pico- or mini-hydropower in running water aquaculture farms to provide electricity for aerators, feeders and other appliances used on the farm. In the case of this type of intervention, in addition to technical aspects, it is also important to consider the need for building knowledge capacity, awareness of and acceptance by the technology users, i.e. fish farmers and other technical staff.

This report will provide examples of renewable energy interventions across small-scale fisheries value chains in the following subsections. Renewable energy interventions can be broadly classified into three types (Figure 27).

► **FIGURE 27**

Types of renewable energy interventions for fisheries



Source: Authors' own elaboration, adapted from FAO and World Fish Center. 2008. *Small-scale capture fisheries: A global overview with emphasis on developing countries.* Washington, DC, World Bank. https://openknowledge.worldbank.org/handle/10986/16752

4.1.1 INTERVENTIONS ALREADY APPLIED TO FISH VALUE CHAINS

These interventions employ renewable energy powered equipment and technologies that are already available on the market. A good example of this is PV powered refrigerators and freezers. These appliances can operate both on-grid and off-grid PV systems with batteries for times when electricity access is limited or not available.

An example of this sort of intervention is a rural women's association that tested solar-powered freezers in the Solomon Islands, where only 48 percent of the population has access to electricity. In addition, access to fisheries centers (centralized fish processing and distribution infrastructure) is not yet possible for most rural people (80 percent of the population lives in rural areas). These women's associations provide solar freezer renting services for cold storage of fish and other perishable foods, to the rural community of Malaita. This project was a breakthrough because refrigeration was made available in this community for the first time. The simplicity of the technology, and possible off-grid operation, allowed the members of the rural women's association to earn enough money to operate and maintain the freezer (all repair costs are recovered). At the same time, they saved money and reduced food losses. In the end, this approach created a renewable energy-based alternative for cold fish storage in remote areas (Agrilinks, 2019).

4.1.2 INTERVENTIONS CURRENTLY APPLIED IN A DIFFERENT VALUE CHAIN BUT ALSO SUITABLE FOR FISHERIES

Equipment using renewable energy is available on the market, but not commonly used in the fisheries value chain. While no reference cases have been reported, this type of equipment could potentially be used at different stages of the fisheries value chain. For example, portable coolers for camping use a PV system that comprises solar panels and batteries. According to their technical characteristics, they could be used for small-scale post-harvest storage in fishing boats and could even serve as equipment for the sale and distribution of fish.

A successful case study of this type of intervention is found in Kenya, where electric bicycles are used for drinking water distribution. These bicycles use electric batteries charged by solar PV systems, which reduces fuel and maintenance costs compared to motorbikes. However, this approach is found to be suitable and can be extended to the transport and distribution of fish products. Manufacturers also provide training on the local production and maintenance of electric bicycles, besides providing charging stations and electric battery rentals facilities (WeTU, 2019).

4.1.3 INTERVENTIONS THAT CAN THEORETICALLY BE APPLIED TO FISHERIES

Other RES, such as biogas and some liquid biofuels such as straight vegetable oils (SVOs), bioethanol, biodiesel and biogas, among others, could in theory power combustion engines. These biofuels could possibly be used across the fisheries value chain in boats, refrigerators, distribution trolleys, machines for aeration and feeding and pumping equipment in aquaculture. Also, tidal and wind energy could theoretically generate large amounts of electricity for mainly marine-type fishing activities, but few cases have been reported on a small scale and are mostly projects still under research (Hydro Review, 2019; Serpetti *et al.*, 2021).

An excellent example of theoretically applicable interventions is found in the 2017 study on biodiesel usage to power a paddlewheel aerator engine in a fish culture tank (Suthisripok and Semsamran, 2018). This study demonstrated the technical feasibility of using liquid biofuels in aeration systems, but no other documented cases and specific availability for that use in the market have been found.

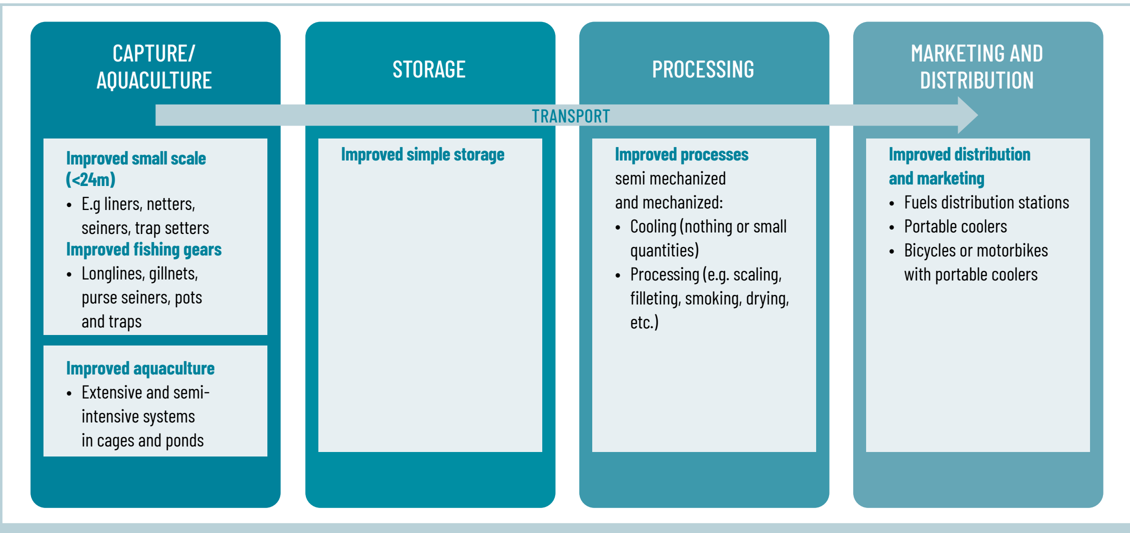
There are also theoretical proposals for offshore multi-purpose platforms for fisheries (multi-purpose fisheries platforms). These systems are intended for tidal, wind and solar energy simultaneously, and seek to provide energy services to marine fisheries and aquaculture systems adjacent to the platform (Hydro Review, 2019; Serpetti *et al.*, 2021; Vassilou *et al.*, 2015).

4.2 OPPORTUNITIES FOR RENEWABLE ENERGY INTERVENTIONS IN SMALL-SCALE FISH VALUE CHAINS

The specific energy interventions in fish value chains based on technology improvements at different stages of the small-scale fish value chain are presented in Figure 28, where improvements in fishing fleet technology and fishing methods at the catch production level are proposed. It is possible to move from solely extensive systems to semi-intensive systems with technologies that can support and optimize fish farming in aquaculture. At the storage level, technologies for ice production could be improved, including equipment for refrigeration, freezing and fish storage. At the processing level, improvements in preservation units (also used in storage), semi-mechanization, and/or mechanization of units for fish gutting, cutting, scaling and filleting, and equipment for drying, smoking and packaging the final product, are a feasible option.

► FIGURE 28

Improved small-scale value chain



Source: Authors' own elaboration.

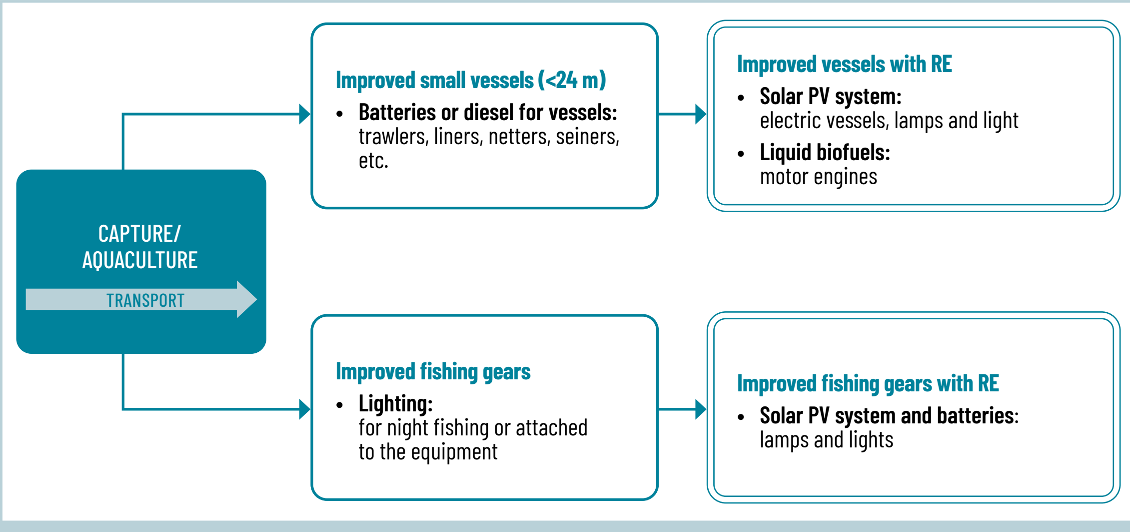
Once the technological improvements are defined, intervention options are proposed at each stage where the energy source can be replaced with renewable energy options.

4.2.1 CAPTURE

Some of the main variables that define small-scale fisheries are the technologies used by fishing fleets, once they have been technologically upgraded. The renewable energy intervention opportunities will require the replacement of the energy sources of electric or diesel engines, following which renewable energy systems can be used to charge electric batteries or directly fuel engines using liquid biofuels (see Figure 29).

► **FIGURE 29**

Opportunities for renewable energy interventions in improved small-scale capture fisheries



Source: Authors' own elaboration.

Night fishing offers another opportunity that does not require mechanization improvements. Lighting and lamps would help fishers increase catches and reduce fishing time at night. These lamps usually use kerosene as fuel but they can be replaced by electric lamps directly charged by PV systems and batteries.

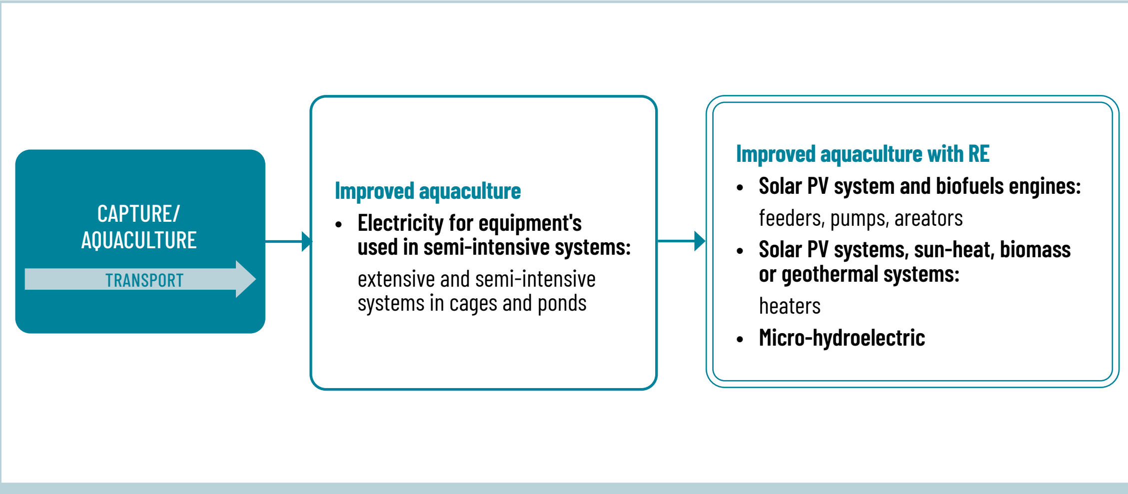
There are several success stories involving the use of these renewable energy interventions. A good example is the effective use of solar lamps for fishing and boat lighting during night fishing in East Africa. Fishers have also reported benefitting from improvements in the quantity and timing of catches (Gengnagel, Wollburg and Mills, 2013). According to experts (Babu and Jain, 2013), the solar PV systems and batteries were integrated into artisanal boats in India to provide sufficient power for lighting, communication instruments, and navigation; furthermore, the application of electromobility in solar-powered boats has been reported by some authors (Torqueedo, 2020; Wilmsmeier *et al.*, 2017). Other renewable energy interventions in capture fisheries will be based on technology modification/improvement, first by replacing manually moved boats with diesel engine boats. Next, diesel fuel will be substituted or blended with sustainable liquid biofuels (i.e. biodiesel or vegetable oils). These biofuels are mainly used for land transport but in theory they can be used after engine modifications in fish boats (Section 4.1.3) (Schroeder, 2015; Lin, 2014; Singh, 2015; Opdal and Hojem, 2007; The FishSite, 2010; Johnson, 2011).

4.2.2 AQUACULTURE

In the case of extensive fish farming, all operations are performed manually. Subsequently, an upgrade to semi-intensive aquaculture will require using larger cages and ponds, automatic pumping systems, feeders and aerators. Most of these units are driven by diesel engines and grid electricity (Muir, 2015). The energy source of this type of automated equipment can be replaced by RES such as PV systems and engines powered by biofuels, such as biodiesel (Suthisripok and Semsamran, 2018).

► FIGURE 30

Opportunities for renewable energy interventions in the improved small-scale value chain for aquaculture



Source: Authors' own elaboration.

Moreover, semi-intensive aquaculture requires heat as a source of energy to maintain suitable temperature conditions for some species. Heating is either produced by boilers running on fossil fuels (e.g. coal or diesel) or directly by using electric heaters, depending on the scale and heating levels needed (Bregnballe, 2015). Heating can also be produced from RES such as geothermal or solar heaters, and biomass-fired boilers running on briquettes, pellets or biomass charcoal fueled boilers. In turn, electric heaters can be supplied using micro-hydro systems and PV systems to generate the required electricity (EIP Energy Service, Nd.; Owani Simo Olok, 2013).

Consequently, the above renewable energy interventions require a previous technology modification/improvement, such as a change from manually moved aquaculture systems to semi-mechanized and mechanized systems. Interventions in aquaculture can also consider the direct substitution of fossil fuels used for heating. In addition, renewable energy interventions are already applied in fisheries (**Section 4.1.1**) and renewable energy suitable for fisheries (**Section 4.1.2**) may be implemented when for example, geothermal energy and micro-hydro systems are used to heat fish ponds and provide the aquaculture system's electricity, respectively.

In aquaculture, some relevant examples of renewable energy use include biodiesel engines and solar PV systems in automatic aeration units. In addition, other authors (Chaithanakulwat, 2019; Suthisripok and Semsamran, 2018) have described and illustrated the use of windpumps and solar pumps (Davies, 2016; Toner and Mathies, 2002). Moreover, geothermal energy utilization for heating in fish ponds such as for salmon, tilapia, seabass, and trout has been presented (Lund and Toth, 2021; van Nguyen and Arason, 2020; Nyambura, 2016; Świątek, 2020). Finally, there are also some projects for the installment of small hydropower systems for recirculating aquaculture systems (EIP Energy Service, Nd.).

4.2.3 AGGREGATION AND STORAGE

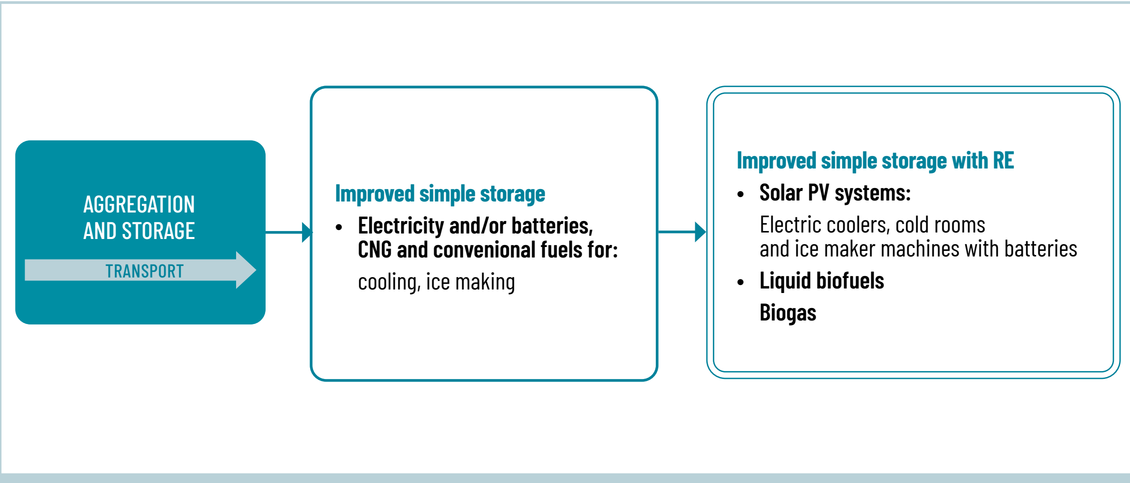
A further option would be to preserve the captured fish as soon as the boats arrive at the port, or when the artisanal fisherfolk return to shore. In this case, aggregation and storage are important for reducing product losses, mainly when the fish are neither processed nor consumed immediately and need to be transported to processing and distribution facilities (Muir, 2015).

Renewable energy interventions can be carried out directly by substituting conventional energy sources used in coolers, chillers, cold rooms or ice-making machines. Examples of technology modification/improvement interventions are available in the case of small-scale fish farmers who gain access to cold storage facilities to refrigerate freshly caught fish. In this case, direct renewable energy interventions can include PV cold rooms, solar chest coolers and solar ice-making machines (Section 4.1.1). Moreover, interventions suitable for fisheries (Section 4.1.2) include absorption chiller technologies where the heat needed in the cooling cycle is obtained from geothermal, solar concentration or biomass boilers (Pushpala, 2016).

Overall, the most simple option for storage is ice containers carried on fishing boats which are used to preserve fish *in situ* when they are transported. First, the renewable energy intervention comprises the improvement of electric ice-making machines that could produce flakes, cubes or blocks according to the fish storage needs. Therefore, the electricity demand of these machines can be supplied using solar PV systems with or without batteries, or biogas/liquid biofuel engines (Figure 31). In addition, fish can be stored in portable chillers or refrigerators with batteries that use solar PV systems for charging (Gänsler, 2018; Muir, 2015). For more extensive periods or volumes of storage, horizontal and vertical refrigerators or chillers are valuable options. RES can also supply the energy demand of these units with solar PV systems or engines running on biogas or liquid biofuels.

► FIGURE 31

Opportunities for renewable energy interventions at the improved small-scale for aggregation and storage.



Source: Authors' own elaboration.

The literature available offers multiple success stories of renewable energy use for storage in the fisheries value chain. Several authors reported the use of PV systems to supply energy to refrigeration rooms, coolers and freezers suitable for storing fish and other agricultural products (Bareiss *et al.*, 2019; IRENA, 2017a; World Fishing & Aquaculture, 2012; Worldfish, 2019). Some fish farmers' associations in Djibouti, Bulgaria and Albania, have projects to develop collection centres based on renewable energy-powered cold storage technologies (FAO, 2021d). PV-based ice-making machine projects have been demonstrated in Senegal (Gänsler, 2018) and Kenya (Bareiss *et al.*, 2019).

4.2.4 PROCESSING

For artisanal and small-scale value chains, fish processing combines manual and traditional fish cleaning, drying and smoking. Hence, at this scale some improvements are needed to create room for renewable energy interventions. Technologies comprising mechanized and semi-mechanized unitary operations add value to final products and extend their shelf life for sale in local or regional markets. Thus, slaughtering, deheading, gutting, filleting, scaling and packaging fish are value-added processing steps that can be improved by using electric machinery. In renewable energy interventions these machines can use energy generated by solar PV systems, with or without batteries, and biofuel-based engines (see **Figure 32**).

- **Drying and smoking**

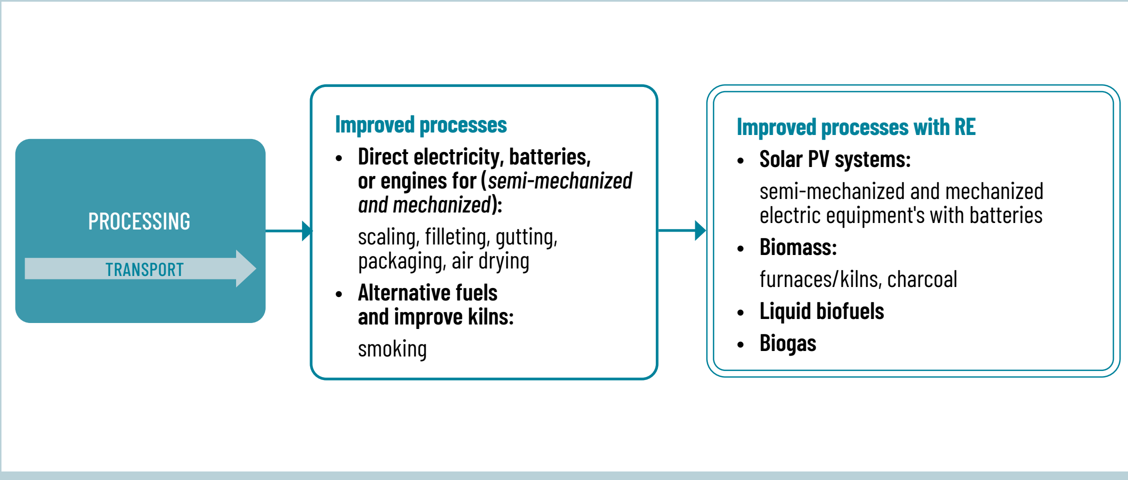
  Smoking and drying fish are the most commonly used methods of fish processing at the artisanal or small-scale level. These technologies are based on traditional smokers fired with unsustainable charcoal and firewood (FAO, 2021d). However, field experts have reported technical problems with traditional smokers regarding their design and operation, added to which they are known to emit significant carcinogenic polycyclic aromatic hydrocarbons (PAHs) (Mindjimba, 2020). Thus, direct renewable energy interventions for fish smoking should first tackle the fuel issue and comprise a combination of more efficient kilns and cleaner fuels – needing modification/improvements in system design and materials – and increase efficiency, as has been advised by experts (Gebrezgabher, Amewu and Njenga, 2018).

  Optimized kilns can capture most of the heat and smoke produced while reducing overall fuel consumption. Examples of the renewable energy interventions comprising the points mentioned above are framed within the "already applied in fisheries" (**Section 4.1.1**) category. Improved kilns for fish smoking, including the FAO-Thiaroye fish processing technique (FTT) and Chokor kiln, have been reported as successful case studies. Notably, the use of FTT in 15 sub-Saharan countries such as Angola, Ghana and Côte D'Ivoire has been documented. FTT technology has been analysed in combination with agricultural residues such as coconut shells and husks as fuels. Authors found that this combination can reduce PAH emissions compared to traditional firewood used in these countries, such as rubber and mangrove wood (Mindjimba, 2020). In turn, the Chokor kiln, which is widely used in Africa, is also recognized as an improvement in fish smoking technology. Compared to the traditional technology, the Chokor resulted in more efficient smoking and consumes less fuel, which when combined with alternative solid biofuels usage, would decrease emissions of PAHs, as does the FTT (Akinwale, 2019).

  Moreover, cleaner fuels such as crop residues-based briquettes, pellets or charcoal can replace traditional fuels while maintaining the organoleptic properties of the final product (Bomfeh *et al.*, 2019; Mindjimba *et al.*, 2019; Mindjimba, 2020; Ndiaye, Sodoke Komivi and Diei-Ouadi, 2015). Especially in the case of briquettes for fish smoking, briquettes from agricultural residues such as mellon shell (Umar *et al.*, 2018) and water hyacinth (Davies and Davies, 2013) have been reported.

► **FIGURE 32**

Opportunities for renewable energy interventions in improved small-scale processing



Source: Authors' own elaboration.

Fish drying is traditionally performed via direct sun exposure. However, this approach is highly dependent on weather conditions and air humidity. Therefore, in those cases where a high-quality product is needed, improved drying technologies are necessary.

Usually, the renewable energy interventions for drying require the modification/improvement of existing technology. A simple technology variation is solar drying tunnels which permits an even heat distribution through the channel while protecting the product from the environment (Lingayat, Balijepalli and Chandramohan, 2021). Another improvement for drying tunnels is to use solar PV systems to supply the electricity demand of fans that facilitate air circulation inside the tunnel, or the use of solar air heating systems. Similarly, fish drying can be carried out in an electric oven, which in turn can be supplied by using PV systems and engines running on biogas and liquid biofuels.

The scientific literature presents a number of examples of renewable energy that is already applied in fisheries (Section 4.1.1), and applications that are also suitable for drying fish (Section 4.1.2). In the first case, an example is drying as part of fish processing, where authors reported the use of renewable energy sources such as solar PV and geothermal energy to power drying systems (van Nguyen and Arason, 2020). In addition, local experts reported drying tunnels using geothermal heat in Iceland (van Nguyen and Arason, 2020). In the second case, an example is the drying of lime, fruit and other agricultural products by a system that runs on liquified petroleum gas (LPG). These options may also be powered by solid sustainable biofuels (i.e. briquettes, pellets) as several authors have reported (Suherman *et al*., 2020; Janjai, 2012; Sethi and Dhiman, 2020; Hamdani Rizal and Muhammad, 2018; Samuel *et al*., 2019).

- **Technologies for value addition**

At artisanal and small scales when fish is not sold immediately after catching, some level of processing is possible. It is mainly carried out manually using simple tools for slaughtering, deheading, gutting, filleting, scaling and packaging the fish. In addition, it is possible to find some chilling or cooling operations as soon as processing occurs, which usually ends with some basic form of freezing of the fish for subsequent distribution and sale. Renewable energy interventions for processing would first need "technology modification/improvement". Thus, all manual operations should first be transformed to semi-mechanized or mechanized slaughtering, deheading, gutting, filleting, scaling, and packaging machines. This intervention will increase production capacity and processing quality while reducing waste and fish losses (Kruijssen *et al.*, 2020). Once this technological change happens, renewable energy can supply the electricity demand. At the moment, it has not been possible to find evidence of renewable energy applied to these interventions, but in theory renewable energy can be applied as biofuel-driven engines or solar PV systems (Section 4.1.3). In the case of chilling and freezing units, the renewable energy interventions are already applied in fisheries (Section 4.1.1) and are well documented. Several authors reported the use of solar chest freezers, solar cold rooms and freezing rooms, blast freezers, among others in fish value chains (IRENA, 2017a; Thomson Reuters Foundation, 2017; Gänsler, 2018; Murithi, 2019; PCREEE, 2019; Worldfish, 2019; Freecold, 2020; Knodt and Kimani, 2020; GIZ, 2021).

4.2.5 MARKETING AND DISTRIBUTION

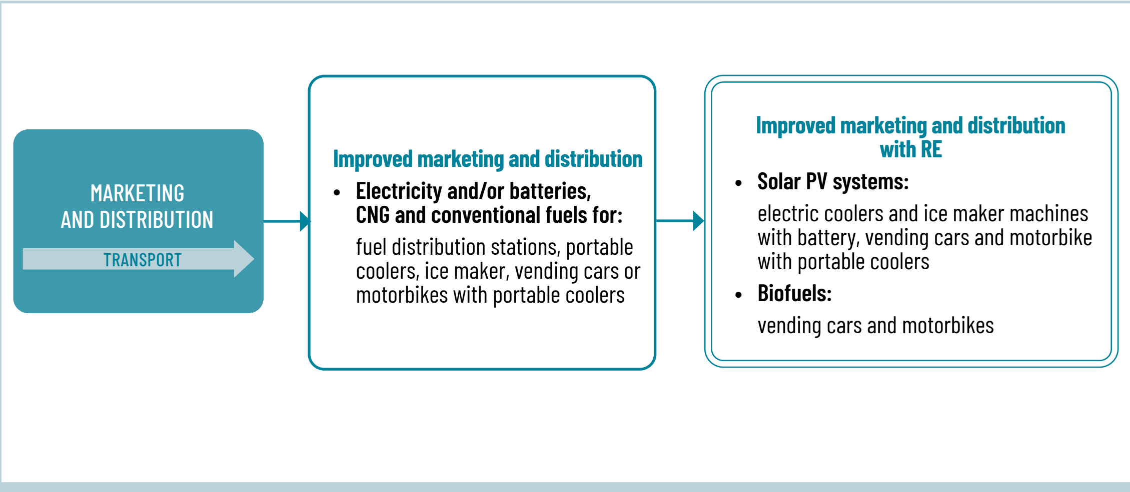
In artisanal and small-scale fisheries, simple fish marketing and distribution might be the next step after catching or processing; making technological improvements at this stage is essential for preserving the product and consequently increasing its shelf life.

When fish farmers sell fish fresh, ice is often used at a small-scale level for preservation when there are inadequate storage or distribution systems, either preliminarily and/or post-processing. The selling point is commonly located at the port where the landing takes place, but fish can also be sold and/or distributed to nearby communities or surrounding markets. Inland distribution and transport across the fish value chain are carried out on foot or in motorized or non-motorized vehicles.

These systems could be technologically improved by using portable coolers, freezers, ice-making machines and trolleys with or without integrated coolers or freezers for the distribution and trade of the product (Figure 33). This equipment commonly uses grid or fossil fuel-fired engines to generate electricity (Muir, 2015), and may be replaced by renewable energy systems.

▶ **FIGURE 33**

Opportunities for renewable energy interventions in improved small-scale marketing and distribution



Source: Authors' own elaboration

Renewable energy interventions at the marketing and distribution stage might require a "previous technology modification/improvement". In the case of the sale of fresh fish, technology improvements should first consider the transition to locally produced ice (using icemaker machines) or the use of coolers and/or freezers. Next, the conventional electricity source of this equipment, which is on-grid or fossil fuel-based, can be substituted by RES (Muir, 2015). Renewable energy interventions can also be made directly since the use of ice, chest coolers or freezers is already known to some small-scale fishers and fish farmers. Solar-freezer, solar-cooler and solar ice-making machines are already using solar PV systems and applied cases have been reported (**Section 4.1.1**). Some renewable energy interventions, such as biofuels that can replace or complement diesel in engines, are suitable options for fisheries (**Section 4.1.2**). Depending on the local availability and selected technology, electricity could theoretically be supplied using geothermal, hydro, and wind energy (**Section 4.1.3**).

In the case of distribution and transport, renewable energy interventions should first consider a transition from on-foot to vehicle usage, both motorized and non-motorized, in those areas where they are not being used. The use of vehicles can expand the area of fish distribution and sales and increase the income of fishers, fish sellers and distributors, while reducing losses from catch and sale. Bicycles, motorcycles, wheelbarrows, trolleys with or without integrated coolers or freezers, small trucks (refrigerated and/or insulated trucks) and pickup trucks are vehicles that can use energy for lighting, mobilization and even refrigeration. This energy is supplied manually or mechanically (bicycles) or from gasoline/diesel engines in some cases. The use of conventional batteries is also a common practice. Therefore, along with the fish value chains where vehicle-based transportation is already in place, switching conventional energy sources to renewable energy would be an appropriate option.

The use of biofuels in engines and solar PV systems to generate electricity for lighting, recharging electric batteries and systems such as coolers and freezers (portable or non-portable), are already available on the market for distributing and transporting different products. Hence, these can be considered as suitable interventions (**Section 4.1.2**) to be applied in fisheries.

Kenya represents a successful case where E-mobility uses PV-charged batteries to distribute drinking water containers on electric bicycles in rural locations. Charging centers for batteries have been established and jobs related to the local production of bicycles have also been created. Motorcycles are expected to be included in the near future. Fishers, farmers and small entrepreneurs can also apply these solutions to their local markets (WeTu, 2019).

Similarly, the use of solar vending food carts in Uganda has been reported by local experts. These vending carts are equipped with an "eco-friendly" stove, light bulbs and phone chargers, all powered by a solar panel. In addition, they can be obtained by a rent-to-own system that includes training for managing a business (Jackson, 2017). Another example is in India, where solar-powered tricycles are used to sell fruit and vegetables. These tricycles are equipped with a chamber for storage under hygienic and evaporatively cooled conditions to keep the food fresh. A 750 WDC geared motor powers the tricycle. A voltage controller and Lithium-Ion battery of 24 Ah is used to store solar power to source DC power (ICAR-IIHR, 2021).

5. TECHNOLOGY SPECIFICATIONS AND COSTS

5.1 COST OF RENEWABLE ENERGY SOURCES TECHNOLOGIES

Table 12 presents the costs for the different RES that have been analysed. The initial investment refers to the price of the equipment, as well the labour and installation costs, while the O&M costs are connected to the annual O&M expenses of the system. For each RES, the costs are presented for the different technologies, while also distinguishing the prices for separate capacities. Generally, the investment and O&M costs decrease as the size of the installation increases.

► **TABLE 12**

Typical installed and operating and maintenance costs for renewable energy sources

RES	TYPE	CAPACITY/ SIZE	INITIAL INVESTMENT USD/kW	O&M COSTS USD/kW/yr	SOURCE
Solar Energy	PV residential	<10 kW	1 325	15.7	DEA, 2021
	PV commercial	10 kW–1 MW	938	13.4	DEA, 2021
	PV utility	>1 MW	621	10.3	DEA, 2021
	District heating	Area 1–2 ha	529[e]	110[d]	DEA, 2021
	Residential solar heating	2–10.5 kW	1 422	46.8[d]	Perers *et al.*, 2017
Wind Energy	Onshore	Utility (>2 MW)	1 312	16.4	DEA, 2021
		Residential (<25 kW)	4 450	111	DEA, 2021
	Offshore (approx. 7 MW)	Far from shore	2 495	46.8	DEA, 2021
		Near the shore	2 050	42	DEA, 2021
Bioenergy	Pellets	40 kg/h	50[a]	0.025[c]	FAO, 2021c
		400 kg/h	20[a]	0.014[c]	FAO, 2021c
		4 000 kg/h	9[a]	0.011[c]	FAO, 2021c
	Briquettes	40 kg/h	48[a]	0.039[c]	FAO, 2021c
		400 kg/h	24[a]	0.011[c]	FAO, 2021c
		4 000 kg/h	6[a]	0.009[c]	FAO, 2021c
	Biogas	80 kW	3 200	560	FAO, 2021c
		300 kW	3 000	450	FAO, 2021c

(Cont.)

RES	TYPE	CAPACITY/ SIZE	INITIAL INVESTMENT	O&M COSTS	SOURCE
			USD/kW	USD/kW/yr	
	Biogas	800 kW	2 600	390	
		1 200 kW	2 500	370	
	SVO generator	10 kW	1 100	816	
		40 kW	980	600	
		100 kW	900	500	
	Biodiesel	5 million L	1.60[b]	0.27[b]	
		25 million L	0.84[b]	0.17[b]	
		50 million L	0.63[b]	0.16[b]	
		100 million L	0.48[b]	0.15[b]	
	Ethanol	5 million L	1.05[b]	0.22[b]	
		25 million L	0.71[b]	0.16[b]	
		50 million L	0.60[b]	0.15[b]	
		100 million L	0.50[b]	0.14[b]	
Hydropower	Large	>10 MW	2 250	45	IEA, 2010; IFC, 2015; NHA, 2021; Energypedia, 2016
	Small	1–10 MW	4 500	112	
	Micro	< 0.1 MW	5 000	125	
	Pico	< 5 kW	1 000–3 750	25–100	
Geothermal	Electricity	Utility	3 916	0.01–0.03[d]	EERE, 2021g; IRENA, 2020
	Residential geothermal heat pumps	8.75 – 17.5 kW	3 071	83.4	Dandelion Energy, 2021
	District heating (>10 MW)	1 200 m depth 80/40 °C	3 178	26.5	DEA, 2021
		1 000 m depth 80/40 °C	3 378	28.0	
		1 200 m depth 70/35 °C	3 168	27.2	
		1 000 m depth 70/35 °C	3 378	28.7	

[a]=USD/l.
[b]=USD/kg/h.
[c]= USD/kg.
[d]=USD/kWh/yr.
[e]=USD/MWh/yr.
Source: Literature cited in table.

Solar PV installations display one of the lowest costs compared to other RES. Residential systems, with a capacity of less than 10 kW, require an initial investment of more than USD 1 000 per kW of installed capacity, while the O&M expenses are approximately 15 USD/kW per year. The overall costs decrease for commercial and utility scale installations, where the investment becomes USD 938/kW and USD 621/kW respectively. Large-scale solar heating systems, used for district heating applications, require nearly USD 530/MWh/year in initial investment. On the other hand, residential systems that occupy between 3 m^2 and 15 m^2 of land have a cost of approximately USD 1 400/kW, with more than USD 45/kWh in annual O&M costs.

Large-scale offshore wind energy installations are more expensive than onshore systems. The latter requires approximately USD 1 300/kW as an initial investment, with the O&M costs reaching USD 16.4/kW/year. More than USD 2 000/kW are needed for offshore systems, with the price rising as the distance from the shore increases, due to higher complexity in the transmission infrastructure, the connection to the grid and the maintenance of the equipment. Domestic wind turbines (i.e. less than 25 kW) display much higher costs, at USD 4 450 per kW.

For a pellet production facility, as the output increases from 40 kg/h to 4 000 kg/h, the initial investment decreases from USD 50/kg/h to USD 9/kg/h, with the O&M costs ranging from USD 0.025/kg to USD 0.011/kg respectively. The costs for a briquetting installation display similar trends but are somewhat lower. The investment required for a biogas generation plant can range from USD 2 000/kW to USD 2 500/kW for respective capacities of 80 000 and 120 000 kW, while for the production of SVO the initial investment ranges from USD 1 000/kW to 900 000/kW for a 10 kW and a 100 kW plant respectively. Biodiesel is slightly more expensive to produce compared to ethanol. A biodiesel production plant with a capacity of 5 million litres displays an initial investment of approximately USD 1.6/L, while a larger installation of 100 million litres costs USD 0.48/L. The respective costs for ethanol production are USD 1.05/L and USD 0.50/L.

Large-scale hydropower plants require an initial investment of more than USD 2 000/kW and have annual O&M costs of approximately USD 45/kW. Small and micro-scale installations are generally more expensive as the investments are USD 4 500 and USD 5 000/kW, respectively. Pico-hydropower with capacities less than 5 kW, display costs that range between USD 1 000/kW and USD 3 000/kW.

Geothermal power plants for electricity generation are usually large-scale systems, where the initial investment is nearly USD 4 000/kW and the annual expenses for O&M are between USD 0.01/kWh and USD 0.03/kWh. For geothermal energy systems in district heating grids, the costs depend on the depth of the reservoir and the temperature of the geofluid. Generally, deeper reservoirs result in bigger investment and O&M costs. Lastly, geothermal heat pump installations for residential applications cost more than USD 3 000/kW and their annual O&M expenses are USD 83/kW/yr.

5.2 TECHNOLOGY SPECIFICATIONS

At every step of the fisheries value chain, a wide variety of equipment is used. In most cases, equipment is either powered directly by electricity (e.g. fish scaling machine), or by batteries (e.g. lights on a boat). In both instances, RES can be used to generate electricity which may either provide direct power for the equipment or be used to charge a battery system. Generally, electricity can be produced both on-grid and off-grid using RES. The conditions, characteristics and RES potential of a location are the main factors that should be taken into account in order to determine the most appropriate RES for a specific application.

For all types of equipment, several parameters have to be established, such as size, power, voltage, materials and market price. Based on the energy requirements, it is also possible to determine the technical characteristics of the energy system that will be used to power the equipment. Using solar PV systems to generate electricity is a very common choice, especially for small-scale off-grid applications. Within this analysis, a PV system is assumed to be the source of electricity for all types of equipment that are powered by electricity, without setting aside other common power sources such as biofuels or biogas-driven motor engines. Various characteristics have to be defined, such as the nominal power, efficiency and type of PV panels, the specifications of the inverter and the maximum power point tracking (MPPT) system, as well as the energy storage (i.e. battery) system. The type of batteries, their nominal voltage and capacity, their losses and depth of discharge are vital factors that also need to be determined.

After defining the technical characteristics of the PV system, it is possible to calculate its cost, with some important considerations. Firstly, an off-grid system is generally more expensive because batteries are required to ensure that demand can be met at any given time. Additionally, an AC system presents higher costs than a DC system. PV panels generate DC currents and a DC/AC inverter is required in the case of AC equipment, thus adding to the overall costs. Lastly, in areas with lower solar energy potential (i.e. low irradiation), a larger number of PV panels is required to generate the same amount of electricity than a smaller number of panels in a location with abundant solar resources. Consequently, for a specific application, sizes, capita investment and O&M costs of the solar PV system increase as the solar energy potential of the location decreases.

For all types of equipment that can be powered by renewables in the fisheries value chain, specifications are defined and presented in detail in the **Appendix**. Some examples are provided in **Section 5.3** and **Section 5.4** as a reference for the methodology and approach.

5.3 EXAMPLE 1: SOLAR FREEZERS IN RURAL FISH FARMER COMMUNITIES

Solar-powered freezers are equipment in which energy demands are supplied using solar PV systems. The generated electricity can be supplied either on-grid or off-grid. In the first option, PV systems are usually employed as a backup. In contrast, off-grid systems must store electricity in batteries, which in turn are connected to the freezer.

In a typical fish value chain, solar freezers can be used at the processing stage to preserve processed fish (after cleaning, scaling, filleting and packaging). Also, the distribution and marketing stages require freezing for preservation of the product during transport and final sale.

There are different solar freezer set-ups available in the market, e.g. upright freezers, blast freezers, deep freezers or chest freezers. The latter option is among the most frequently used in fish value chains because of the perceived energy efficiency of chest freezers compared to upright freezers.

Other important technical features are the target capacity and freezer temperature. These features allow for sizing the freezer and will ultimately define the fish preservation properties.

On the other hand, refrigerant type and ambient temperature are features that impact refrigeration efficiency. At the same time, weight and defrosting methods are essential features when considering equipment installation and maintenance.

Finally, power and voltage are energy demand parameters that allow a potential user to define the electricity requirements for operation. These last two specifications are key for designing the photovoltaic system used for the freezer energy supply.

5.3.1 CASE STUDY: THE COOL WOMEN OF MALAITA

The case study mentioned in **Chapter 4** is presented as an example. In the rural community of Malaita in Solomon Islands, a women's group received a solar-powered freezer in order to provide fish preservation services to small-scale fisher families in the area (Worldfish, 2019). It was not possible to obtain the technical details of this case study, but the example demonstrates a set-up very similar to the one reported, using a horizontal freezer of 118 L capacity. Technical and cost specifications were obtained from data available in the market, and these are presented in **Table 13**.

► **TABLE 13**

Technology specifications and cost for chest freezer

TYPE	CHEST, HORIZONTAL, DEEP FREEZER
Capacity [L]	118
Power [W]	60
Voltage [V]	AC:220–240V, DC:12/24V
Refrigerant	R134a
Temperature for freezer [°C]	≤ –18
Gross Weight [kg]	29
Defrost	Manual
Price [USD]	583

Source: Jumia. 2021. Bona 118L white solar freezer. In: *Jumia*. Cited 31 January 2022. www.jumia.com.ng/bona-118l-white-solar-freezer-73126318.html.

► **FIGURE 34**

Example of a solar cooler/freezer

Source: WorldFish Flickr. 2018. Woman in Surairo, Solomon Islands holds up fish from a solar freezer. In: *Flickr*. Cited 21 April 2022. www.flickr.com/photos/theworldfishcenter/46372939685/in/photostream

5.3.2 RENEWABLE ENERGY INTERVENTION: SOLAR PHOTOVOLTAIC SYSTEM

In keeping with the above example, Table 13 presents information on the power and voltage demand for a 118 L freezer. The energy demand of these freezers is met by solar power. The solar resource availability information was assessed based on the Solar Global Atlas for Malaita. It is based on a PV power output of 3.358 kWh/kWp per day; an average ambient temperature of 26.9 °C; an optimum tilt of PV modules of 9 °; and 12 hours of sunshine on average per day (Global Solar Atlas, 2021c).

Table 14 shows the technical specifications for an optimized solar PV system design at Malaita. It considers using a 325 W monocrystalline solar panel with at least 19.56 percent efficiency per module. Other parameters on inverter design and batteries for energy storage when required are also included.

► **TABLE 14**

Technical specifications, investment and running cost for solar freezer PV systems

SOLAR PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	325
Max. power voltage (Vpm) [V]	33.5
Open circuit voltage (VoC) [V]	40.3
Module efficiency [%]:	19.56
Minimum number of panels needed [modules]	1
Cost [USD/unit]	155
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716. ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Peak efficiency [%]	98
Cost [USD/unit]	98
INVERTER DATA	
Capacity [kW]	0.4
Max voltage [V]	54
Power factor	0.99
Number of inverters	1
Cost [USD/unit]	181
BATTERY DATA	
Type	Lithium
Battery losses [%]	15
Depth of discharge for battery [%]	40
Nominal voltage [V]	25.6
Nominal capacity [Ah]	20

(Cont.)

BATTERY DATA	
Number of batteries	3
Cost [USD/unit]	580
Certifications	IEC 61 427, CE, IEC 60 896

Source: Authors' own elaboration.

From the technical specifications proposed, the capital O&M costs were calculated (Table 15). The capital costs include i) equipment costs (panels, batteries, inverters and system controllers); and ii) building and installation costs (civil and electrical, array structure, freight and transport). O&M comprises operational and maintenance costs to run the PV systems. The O&M costs also included a loan payment to cover the capital costs. The loan interest rate for Solomon Islands in 2020 was 10.68 percent (World Bank, 2021).

The obtained results are presented for off-grid and on-grid systems, considering the difference in design and equipment that both options have (see Table 15). Thus, off-grid systems usually involve batteries and charge controllers (MPPT) in addition to the solar panels and cables, so that the freezer can operate at night, and on cloudy or low irradiation days. It is a critical feature in off-grid, isolated areas. In on-grid systems, the energy is supplied from solar panels and grid electricity. In this case, batteries and MPPT controllers are usually not considered which significatively reduces capital costs.

Finally, the freezer might run on alternating current (AC) or direct current (DC). An inverter is needed in the first case because batteries operate in DC. In the case of off-grid installations, when a freezer runs on DC, inverters are excluded. Even so, the design must keep charge controllers to regulate the electric current supply from the batteries. In on-grid installations, inverters between batteries and freezers are required.

The same cost structure is used for other relevant renewable energy equipment suitable for use in the fish value chain (see Appendix).

► TABLE 15

Investment and running cost for solar chest freezer

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED[a]	DC SYSTEM/INVERTER EXCLUDED[b]
Total capital cost [USD]	2 271.3	2 090.33
O&M costs [USD/kWh]	0.26	0.25

[a] AC system: panels: 1, inverters:1, batteries: 3.
[b] DC system: panels: 1, batteries: 3.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED[a]
Total capital cost [USD]	433.33
O&M costs [USD/kWh]	0.13

[a] AC system: panels: 1, inverters: 1.

Source: Authors' own elaboration.

In the specific case of the Malatia women's association, the solar freezer is off-grid (Worldfish, 2019). In addition, it can be assumed that the freezer is an AC model. According to the results presented in Table 15, it can be estimated that the PV system will have a capital cost of USD 2 271. The PV system comprises one solar panel, one inverter and three batteries, with the latter responsible for the capital cost increment compared with an on-grid system. The O&M costs for this system were USD 0.26/kWh, resulting from additional capital costs and, consequently, additional loan payments for an off-grid system. Thus, the results also show that if this freezer operated on-grid, the investment costs would be reduced fivefold, and the O&M costs would be halved, compared to off-grid operation. As mentioned in the background paper (Worldfish, 2019), this possibility is not yet feasible for this and other rural communities in the Solomon Islands. However, the background paper's authors stated that the total capital and O&M costs could be recovered in the medium term because of the efficient and organized use that the women's groups in Malaita have made of the freezer and its services.

5.4 EXAMPLE 2: SOLAR FISHING LIGHTS IN LAKE VICTORIA

Solar fishing lights and lamps are used for lighting during night fishing, and their electric batteries are recharged using solar PV systems. The solar PV charging stations must operate off-grid due to the fact that they are primarily used during fishing trips. According to the study conducted by Mills, Gengnagel and Wollburg (2014), solar lights and lamps yield improved catches when used to attract fish at night, and also allow for better visibility during night fishing (compared to paraffin lamps). There are different types of battery-powered lights and lamps available on the market for specific use in fisheries. Some of them are part of applied studies, such as the one conducted in Lake Victoria (Gengnagel, Wollburg and Mills, 2013). These devices typically use light emitting diode (LED) lights or waterproof halogen lights. Some lights are used to illuminate boats, some are integrated into fishing nets, and some can be submerged to improve visibility and catchability. The luminous flux, the type of lamp and the materials are technical parameters that define the capacity and use of lamps and fishing lights. Similarly, parameters such as power and voltage determine the energy needed to charge the batteries fully.

5.4.1 CASE STUDY: THE LUMINA PROJECT – LAKE VICTORIA, EAST AFRICA

As an example, we present the case of The Lumina Project, a field project developed in different artisanal and small-scale fishing communities in Lake Victoria, East Africa. This project proposed using LED and halogen lights to replace the paraffin lamps traditionally employed in night fishing.

Gengnagel Wollburg and Mills (2013) indicated that night fishers in this African region, particularly on the Tanzanian side of the lake, use approximately 35 percent to 50 percent of their income for lighting expenses (fuel plus maintenance costs). Therefore, during this study it was shown that similar catches could be obtained by using battery-powered LED lighting systems, while eliminating fuel costs. In general, at the close of the project, fishers were satisfied and willing to use battery-powered solar lights, provided that the price and performance were acceptable. In an effort to illustrate the technical specifications of this case, approximate technical and cost parameters were obtained for the Aqua Star Super Brite 192 LED lights model, which is referenced in the study. The technical data are presented in Table 16.

► **TABLE 16**

Technology specifications and cost for fishing lights

FISHING LIGHTS	
Lantern type	White LED
Power consumption [W]	26.5
Operating Voltage [V]	12
Lamp luminous flux [lm]	1302
Beam angle (degree)	120
Operation	Underwater
Materials	Aluminium
Price [USD]	104

Source: AlumiGlo. 2021. Fishing lights-Superbrite 2500-X2. In: *AlumiGlo.* 21 April 2022. https://www.fishinglightsetc.com/products/fishing-lights/superbrite-2500-x2/

5.4.2 RENEWABLE ENERGY INTERVENTION: SOLAR PHOTOVOLTAIC SYSTEM

In the project implemented at Lake Victoria, a solar PV system is recommended as a method to charge the electric batteries used by the fishing lights and lamps. Furthermore, it is possible to take advantage of the fact that some fishers already use lamps with batteries and are familiar with the recharging operation. The project concluded that installing and using a solar PV charging system would be easy to adapt. Moreover, the fishers themselves prefer this type of solution (Gengnagel, Wollburg and Mills, 2013).

An optimized design for a system that could charge the fishing light batteries according to local solar resource availability, is presented in Table 17. This proposal is based on information from the Solar Global Atlas for Lake Victoria-United Republic of Tanzania, where a specific photovoltaic power output of 4.453 kWh/kWp per day; an average ambient temperature of 23.5 °C; an optimum tilt of PV modules of 4 °; and 12 hours of sunshine on an average per day were identified (Global Solar Atlas, 2021d).

In Table 17, the technical data and costs related to the proposed solar PV system's design are presented. This optimized design proposal considers using one 195 W monocrystalline solar panel with at least 19.67 percent module efficiency. The proposal includes parameters on designing an inverter for DC/AC operation and batteries for energy storage.

► **TABLE 17**

Technical specifications, investment and running cost for solar lamp/fishing lights photovoltaic systems

SOLAR PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	195
Max. power voltage (Vpm) [V]	21.4
Open circuit voltage (VoC) [V]	24.3
Module efficiency [%]:	19.67
Minimum number of panels needed [modules]	1
Cost [USD/unit]	145
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716. ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Peak efficiency [%]	98
Cost [UDS/unit]	98
INVERTER DATA	
Capacity [kW]	0.4
Max voltage [V]	54
Power factor	0.99
Number of inverters	1
Cost [USD/unit]	181
BATTERY DATA	
Type	Lithium
Battery losses [%]	15
Depth of discharge for battery [%]	40
Nominal voltage [V]	12.8
Nominal capacity [Ah]	10.5
Number of batteries	2
Cost [USD/unit]	172
Certifications	IEC 61 427, CE, IEC 60 896

Source: Authors' own elaboration.

The annual costs related to the system are presented in Table 18 and show the total capital and O&M costs. For the O&M costs, a 16.68 percent loan interest rate is considered for the United Republic of Tanzania in 2020 (World Bank, 2021).

► **TABLE 18**

Investment and running cost for fishing lights PV system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED[a]	DC SYSTEM/INVERTER EXCLUDED[b]
Total capital cost [USD]	USD 801	USD 620
O&M costs [USD/kWh]	USD 0.26	USD 0.22

[a] AC system: panels: 1, inverters: 1, batteries: 2.
[b] DC system: panels: 1, batteries: 2.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED[a]
Total capital cost [USD]	USD 359
O&M costs [USD/kWh]	USD 0.16

[a] AC system: panels: 1, inverters: 1.

Source: Authors' own elaboration.

Table 18 presents the results of the cost analysis. In the case of Lake Victoria, fishers opted for installing a solar PV system with off-grid operation, according to the concepts of the previous example. Charging stations run on AC. The total capital investment cost would be USD 801, and O&M costs USD 0.26/kWh. Although presenting the highest total capital costs, the off-grid operation using an inverter and two batteries does not differ significantly with regards to O&M costs, and it is an alternative to the use of conventional fuels, in this case paraffin lamps. In fact, this could possibly represent a reduction in fuel costs, with fishers spending more than a third of their income on paraffin in the long term.

6. OPPORTUNITIES AND CHALLENGES FOR RENEWABLE ENERGY INTERVENTIONS

The assessment and review of energy use in the small-scale fish value chain identifies how energy is used in small-scale fisheries and aquaculture, and pinpoints stages within the value chain where renewable energy interventions can be used to increase efficiency and reduce losses. The assessment also identifies technologies that are currently available and which can be deployed along the small-scale fisheries value chain to improve energy access and enable better storage and processing.

Using these technologies can have several environmental as well as socio-economic benefits. Nevertheless, there are also significant barriers to the uptake and adoption of the identified technology options. In addition, it is important to emphasise that agrifood chains are a set of integrated individual activities that span a number of steps that also vary across the different food value chains. Faults at any step of the agrifood chain impact the efficiency and operation capacity of the entire chain. Therefore, the success of the identified technology does not solely depend on the technical potential but is also linked to all actors and processes in other stages of the agrifood chain. To successfully develop a well-functioning modern small-scale fisheries value chain, which has access to dependable and clean energy and that promotes social and economic benefits, all actors across the chain, including policymakers, the private sector, financing agencies and, most importantly, the fish value chain operators themselves need to be included.

6.1 KEY ISSUES FOR MARKET DEVELOPMENT

The key issues and barriers that constrain the uptake and adoption of the identified technology options can be classified into three groups:

1. cost and financing for both renewable energy and equipment used;
2. policy environment and local capacity;
3. awareness and acceptance of technology.

6.1.1 COST AND FINANCING OF RENEWABLE ENERGY EQUIPMENT

The upfront costs for equipment such as solar chillers remain high. Additionally, access to credit from mainstream banks seems to be a challenge. In many developing countries, interest rates on consumer loans can be as high as 15 percent to 17 percent, which makes the cost of capital very high, limiting the ability of consumers to access capital and buy such equipment. This is also true for entrepreneurs who find the cost of capital to be expensive, which in turn drives up the cost of their products.

Given these challenges, a multi-pronged approach is advisable so as to guarantee that access to credit for both consumers and entrepreneurs improves, while ensuring that the cost of credit is affordable.

This would require action from the private sector, donors, banks and government institutions. Private sector players would need to develop innovative financial models such as "pay-as-you-go" or cooling as a service.

Donors can play a vital role in reducing the risk on investment for banks and the private sector to allow scaling up. This could be done, for instance, by providing risk sharing guarantees to banks and/or by blending grants and loans to ensure that investments have a major impact. Furthermore, commercial contracts could be encouraged between the private sector and a public entity or a bank where the donor funds could be used to mitigate the risk of non-payment. This type of guarantee would be instrumental in reducing project risk and thus improve the bankability of the project.

6.1.2 POLICY ENVIRONMENT AND LOCAL CAPACITY

In addition to this, developing government policy that specifically focuses on establishing an enabling environment for the proliferation of clean energy technologies for the fish value chain can be instrumental in encouraging the adoption of these technologies. While several countries have special policies on clean energy, they are not exclusively linked to the agriculture and fisheries industries. A policy that encourages the market development of clean energy products specifically targeting the agriculture and fisheries sector would enable private sector investment and the uptake of technology. For example, easing import duties on equipment that is unavailable in a country could be a useful option, amongst others.

In addition, the operation of renewable energy powered equipment for cooling, chilling and processing requires specific knowledge and skills. There might be a need to address existing skills gaps in the country through extensive training, and capacity building is essential to developing a modern small-scale fisheries chain. Vocational training courses could be created and subsequently introduced on, for instance, solar cold storage and other solar technologies to increase the availability of the local technical capacity to develop and maintain solar technologies for the fisheries value chain. This is essential because the availability of technology alone does not guarantee long-term use and adoption. Locally available, affordable and timely technical assistance is also required. A lack of such assistance erodes user confidence and hinders other users from adopting new technology.

6.1.3 AWARENESS AND ACCEPTANCE OF TECHNOLOGY

Awareness of a technology is a pre-condition for it to be accepted by users. Specific renewable energy powered equipment for the fish value chain is not prevalent in many developing countries. Making entrepreneurs and users aware of the benefits and costs of such technologies could encourage their adoption in developing countries. This could be done, for instance, through developing mobile demonstration units that can be taken to different areas of the country to familiarize the users and entrepreneurs with such products and encourage them to develop and use them.

6.2 RECOMMENDATIONS

Given the identified challenges and the results of the analysis, the following recommendations are made:

Recommendation 1 – cost of financing

- Develop a dedicated policy and enabling framework to stimulate investment in renewable energy-powered equipment for the small-scale fish value chain, especially for chilling and refrigeration.
- Targeted interventions are required to create incentives for investment so as to reduce the economic risk and barriers for investors. Additionally, there is a need to facilitate easy access to commercial financing at affordable interest rates, as well as to provide targeted, finite subsidies for investment in infrastructure, specifically decentralized solar energy solutions for productive use in the agrifood chain. Moreover, financial support is required by the private sector to deploy renewable energy technologies that have been identified for specific value chains. Finally, an integrated policy with targeted incentives should be developed for the supply and demand side to encourage the proliferation of solar technologies for productive use in fisheries and aquaculture.
- The provision of time-bound subsidies to reduce the cost of the systems would encourage both the supply and demand side. Countries such as India have an approximate 40 percent subsidy on solar cold storage, for example. However, a precise subsidy amount and time frame would need to be worked out depending on the circumstances of a country.
- A clear regulatory framework is required to fix preferential import duties on solar equipment like solar mills and cold storage to enable and increase availability, as well as promote competition within the country for other renewable technologies.
- Technologies that have proved to be techno-economically viable in countries could be designated as "priority lending technologies". Priority lending sectors allow banks to provide increased lending capital and preferential lending rates to projects operating in the designated sector. In India for example, the Reserve Bank of India (the central bank) designated the renewable energy sector as a priority lending sector, which allowed commercial banks in the country to lend for 20 years to 25 years instead of 10 years to 15 years, at preferential interest rates.
- Given the high lending rates prevalent in many developing countries (15 percent to 17 percent), cost sharing or co-financing for start-ups seeking to develop solar powered equipment would be necessary. The government, with support from donors and development partners, can provide risk sharing guarantees/credit guarantee schemes (CGS) to banks that are willing to finance such start-ups. This would mitigate the risk of non-payment and encourage lenders to provide credit to entrepreneurs in the country. (CGSs provide guarantees to groups that do not have access to credit by covering a share of the default risk of the loan. In the case of a default, the lender recovers the value of the guarantee.)
- Develop on-lending structures for banks. Many local financing institutions in developing countries lack the information or experience necessary to analyse and understand the viability of renewable energy projects, specifically for productive use in agriculture. Developing screening criteria for energy projects for agricultural use requires an understanding of finance as well as knowledge about the technical aspects of solar energy. This a bottleneck because this type of knowledge is often lacking in commercial banks in developing countries

and therefore, the renewable energy projects for agricultural endeavours are a high-risk endeavour. On-lending structures are represented by an organization (in this case a bank) that lends money that they borrow (in this case from the government or a donor) and pass on to the borrower through a line of credit.

Recommendation 2 – policy and local capacity

- Strengthen the capacity of institutions and organizations to identify, develop and promote renewable energy powered technologies in fisheries and aquaculture value chains.
- While subsidy and credit guarantee schemes would support making renewable energy technologies more affordable, this alone would not be able to sustain the industry. In order to develop a marketing scheme, these technologies would require that various actors work together: farmers, the agrifood industry, logistics companies, technicians and engineering firms specialized in solar energy, as well as the food processing industry. Human capital that can develop, install and service these technologies is key to the sustainable development of this sector.
- Establish a dedicated renewable energy training and development centre to train professionals in developing and maintaining solar PV systems for various purposes, including for agricultural use. In many countries this is part of a national qualifications framework or national quality training framework.
- Support vocational training institutions to design and develop programmes on the use of solar PV and other renewable technologies for productive use in agriculture. Priority areas where such training is required are logistics, maintenance and the operation of solar cold storage, milk chillers and solar milling technologies.

Recommendation 3 – increase awareness

- Increase awareness and demonstration of those technologies that are viable in a specific country and a regional context to increase awareness among small-scale fishers and aquaculture workers.
- Assess and identify context specific renewable energy technologies and equipment that have the potential to be scaled up.
- Undertake demonstration exercises to show renewable energy technologies in small-scale fish farmer communities and raise awareness about the benefits and challenges of using these technologies.
- Develop stakeholder partnerships to engage public and private sector players to jointly increase awareness for all stakeholders. Develop awareness raising campaigns, mobilize public opinion, and ensure the uptake of new solutions.
- This initial level of recommendations should be more deeply developed and subsequently validated in the field. Many of these recommendations will require further analysis and consultations and therefore should not be treated as “ready to implement”.

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8. APPENDIX: TECHNOLOGY SPECIFICATIONS, INVESTMENT AND RUNNING COSTS

This appendix shows examples of the technical specifications and costs associated with renewable energy-based equipment suitable for use in the fish value chain. All of the values were collected from information available on the market. Likewise, with the idea of proposing possible interventions with renewable energies for this equipment, PV systems designs to supply the demand of each piece of equipment are presented. Moreover, the capital and O&M costs are estimated for off-grid or on-grid installation of these PV systems.

In the following section, an example of technical specification data and design and cost parameters is presented. To this end, the solar freezers in Malaita will be used as an example. As explained in previous sections, the solar freezer is typically used to preserve fish freshly caught in Malaita in Solomon Islands. This appendix expands on technical specifications to explore the possibilities of different freezer volumes and locations around the world. The other devices included in this appendix follow the same approach as presented in this example (Section 8.1 to 8.20). According to Table A.1, the capacity of small chest freezers ranges from 30 L to 400 L, and the power demand of these freezers varies from 57 W to 450 W. Chest freezers are widely used in the fisheries value chain (Table A.1) and are considered to be more energy-efficient than upright freezers. The type of freezer configuration, capacity, power demand, type of refrigerant, operating temperature and defrosting are parameters that influence the unit cost of the equipment, so the variability in this value will depend largely on the technical characteristics of the freezer.

► **TABLE A.1**

Technology specifications and cost for solar freezer

TYPE	CHEST, HORIZONTAL, DEEP FREEZER
Capacity [L]	30–400
Power [W]	57–450
Voltage [V]	DC 12/24, AC 100/240
Refrigerant	R600a, R134a
Temperature for freezer [°C]	−12 to −30
Weight [kg]	25–86
Ambient range [°C]	+10 to +43
Defrost	Manual
Price [USD]	155–2 195

Source: Authors' own elaboration.

► FIGURE A.1

Example of a solar freezer

Source: WorldFish Flickr. 2018. Annet and Susan putting fish in a solar freezer at Surairo, Solomon Islands. In: *Flickr.* Cited 21 April 2022. www.flickr.com/photos/theworldfishcenter/47287530981/in/photostream

Table A.2 shows the optimized design for a solar photovoltaic system that can supply the energy required by the freezer under minimum standard conditions, and the irradiation related to the location.

Solar irradiance is a vital parameter that defines the amount of energy from the sun that can be captured by solar panels, and it varies according to the geographical location and/or weather conditions of a particular area over a period of time. The potential to capture and generate energy, mainly according to irradiation, is measured in terms of kWh/kWp, and can be obtained from a Global Solar Atlas for any location.

Moreover, to represent how differences in location will impact the following results, the analysis considers the solar resource availability variation at both high and low solar irradiation, but is still suitable for solar energy utilization. This feature is essential because artisanal and small-scale fishing is carried out across the world and potentially benefits from using renewable energy-based equipment such as the solar freezer.

Therefore, a low irradiation location zone will be represented by an average potential of 3.615 kWh/KWp and annual temperatures of between 4.3°C and 26.2°C. A high irradiation location with an average potential of 4.845 kWh/KWp and annual temperatures between 14.3°C and 28.5°C were considered (Global Solar Atlas, 2021e, 2021f). These irradiation and temperature conditions were taken for the design of all the equipment presented in this appendix.

► TABLE A.2

Technical specifications, investment and running cost for solar portable freezer photovoltaic systems

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	325

(Cont.)

PV SYSTEM	
PV PANELS	
Max. power voltage (Vpm) [V]	33.5
Open circuit voltage (VoC) [V]	40.3
Module efficiency [%]	19.56
Cost [USD/unit]	155
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716 ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	98
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	0.4
Max voltage [V]	54
Power factor	0.99
Cost [USD/unit]	181
BATTERY	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	20– 100
Cost [USD/unit]	2 183
Certifications	IEC 61427, CE, IEC 60896

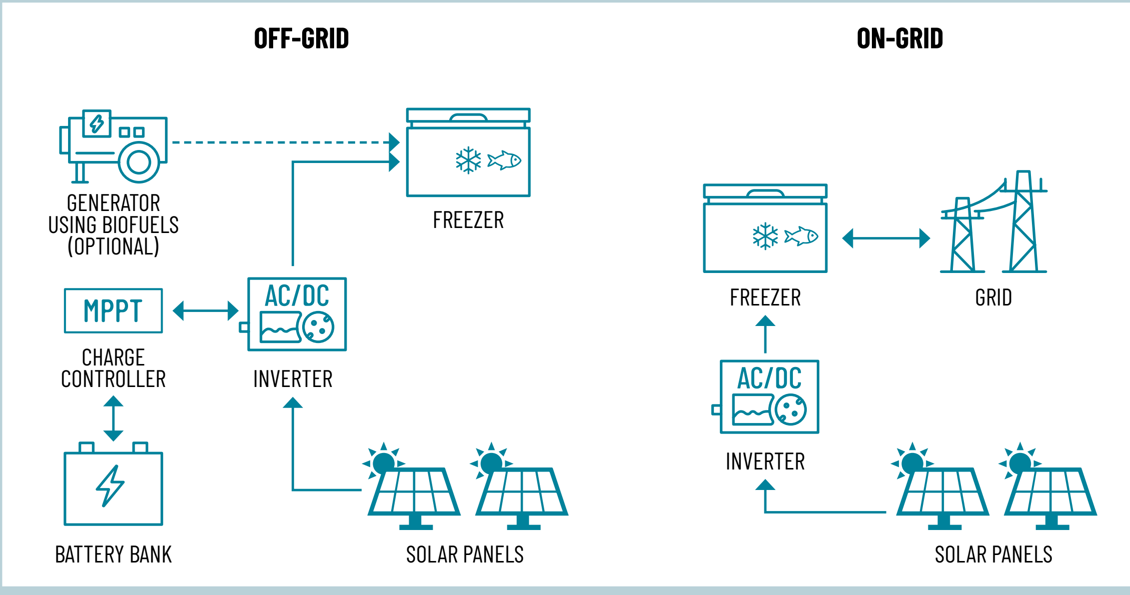
Source: Authors' own elaboration.

Overall, a PV system comprises PV panels, charge controllers (usually a MPPT), inverters and batteries (Figure A.2. See also Section 3.3.1). Specifically, the PV system defined in Table A.2 uses 325 W panels with a 19.56 percent module efficiency. The approximate cost is USD 155 per panel. As for the controller, it is proposed to use a 75 V maximum voltage MPPT to regulate the current received, with an approximate cost of USD 98 per unit. The proposed inverter has a capacity of 0.4 kW and can operate at a maximum voltage of 54 V and convert DC to AC. This unit is important because the panels generate DC, and a typical freezer uses AC; therefore the inverter must first transform DC. The approximate cost of the inverter is USD 181 per unit. It is proposed to use lithium batteries with a nominal capacity between 20 Ah and 100 Ah, which is an indicator of their energy storage capacity. The cost per battery is USD 2 183.

It is worth noting that in order to supply power to a standard freezer, more than one PV module, more than one controller, more than one inverter, and usually more than one battery may be required. In the case where the freezer or other equipment uses DC power, the inverter can be omitted and replaced by other equipment to regulate and transfer the current, but in the case where a hybrid installation is required (to obtain power from the panels and the common grid), it is recommended to keep the inverter to regulate the AC current that usually comes from the grid.

▶ **FIGURE A.2**

Off-grid and on-grid operation for solar freezers



Source: Authors' own elaboration.

In the case of batteries, they can be omitted when the system is on-grid. However, one of the most appealing advantages of solar PV systems is the possibility to operate off-grid and supply power in remote off-grid areas. Next, in the case of an off-grid operation, batteries must store energy when sunlight is available, as solar power availability is reduced in cloudy weather and suspended at night.

Table A.3 presents the optimized investment and operating costs for a solar PV system that can supply the freezer energy demand. The capital costs include i) equipment costs (panels, batteries, inverters and system controllers); and ii) building and installation costs (civil and electrical, array structure, freight and transport). O&M comprises operational and maintenance costs to run the PV systems. The O&M costs also include a loan payment to cover the capital costs, because the loan interest rate changes from one country to another.

Both the total capital and O&M costs vary depending on whether the system is operated off-grid or on-grid. The costs for off-grid systems tend to be higher because they require batteries which have a high cost per unit (compared to the other elements of the PV system), therefore significantly increasing the PV system's total cost. In on-grid operations, the use of batteries is not considered, so costs tend to be considerably lower. Both costs also vary according to the irradiation of the location. Costs in high irradiation areas tend to be lower than in low irradiation areas. Because there is less solar energy availabile in the latter case, there is less power generation per panel. Therefore, the resulting systems will have a higher number of panels, inverters, batteries and controllers to produce the same energy output. Additionally, costs may vary with the use of inverters. For example, when the freezer does not require them, the cost of the inverter and the related O&M expenses should be excluded.

► **TABLE A.3**

Investment and running cost for solar chest freezer photovoltaic systems

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	13 043	12 694	12 862	12 513
O&M costs [USD/kWh]	0.19	0.16	0.19	0.16

[a] AC system – Low irradiation: panels: 7, inverters: 1, batteries: 5.
[b] AC system – High irradiation: panels: 6, inverters: 1, batteries: 5.
[c] DC system – Low irradiation: panels: 7, batteries: 5.
[d] DC system – High irradiation: panels: 6, batteries: 5.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	2 030	1 681
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 7, inverters: 1.
[b] AC system – High irradiation: panels: 6, inverters: 1.

Source: Authors' own elaboration.

All the variations mentioned above are shown in Table A.3. Overall, the solar system designed for the freezer needs seven solar panels, one inverter and five batteries to operate in a low irradiation zone. For operations in high irradiation zones, the system would comprise six panels, one inverter and five batteries. Therefore, the increase in total capital and O&M costs for the system is mainly related to the number of panels in low irradiation zones. Since the power required by the freezer is relatively low, only one inverter is needed to transform the current, so the costs are not significantly affected by this parameter in the case of off-grid operation where batteries are included. It can be observed that there are no high cost variations for high and low irradiation zones, since approximately the same number of batteries is required to supply the freezer energy needs.

The above analysis is conducted for other equipment used in the fishing value chain whose energy demand can be supplied by solar photovoltaic systems. Table A.4 presents a list of the equipment analysed in this appendix and some relevant remarks regarding specific analysis. Technical and cost information for other types of RES, such as for gas engines (biogas) and biofuels engine are also included in this appendix.

► TABLE A.4

List of equipment included in appendix, and remarks

EQUIPMENT	TECHNOLOGY SPECIFICATIONS AND COST	TECHNICAL SPECIFICATIONS	INVESTMENT AND RUNNING COST	REMARKS
Fishing lights and lamps	Table A.5	Table A.6	Table A.7	The PV system is designed as a charging station for electric lamps and batteries. The PV system is small. Low costs are obtained due to the low energy demand of LED lights.
Electric boat motor engine	Table A.8	Table A.9	Table A.10	Electric motors are outboard type. The solar PV system's high costs are related to the high energy demand of motors. As a result, an increased number of batteries is needed.
Solar aerator	Table A.11	Table A.12	Table A.13	This equipment is already available in the market, including solar panels. Aerators can be fixed at one point in the farming lake or moved automatically over the entire surface integrated with the solar PV panels. The use of biofuels such as biodiesel for the engines in these aerators is also under study.
Solar automatic fish pond feeder	Table A.14	Table A.15	Table A.16	Like aerators, automatic feeders are already commercially available and can be fixed or mobilized around the lake.
Solar water pump	Table A.17	Table A.18	Table A.19	The solar PV system's high costs are related to the high energy demand. An increased number of batteries is needed.
Ice making machine	Table A.20	Table A.21	Table A.22 Table A.23 Table A.24	The three main types of ice making machines for flake, cube and block ice production are presented. The solar PV system's high costs are related to the high energy demand. An increased number of batteries is needed.
Portable freezer	Table A.25	Table A.26	Table A.27	It is portable equipment with low energy demand and therefore the associated solar system cost is low.
Solar cold storeroom	Table A.28	Table A.29	Table A.30	The high-cost PV system is explained by the high energy needed for freezing fish on a large scale.

(Cont.)

EQUIPMENT	TECHNOLOGY SPECIFICATIONS AND COST	TECHNICAL SPECIFICATIONS	INVESTMENT AND RUNNING COST	REMARKS
Fish smoker kilns		Table A.31		Reference costs for the use and operation of kilns fueled by wood/charcoal/pellets.
Electric smoker	Table A.32	Table A.33	Table A.34	The electric smoker has a fuel entrance for wood/charcoal/pellets.
Electric drying machine	Table A.35	Table A.36	Table A.37	The solar PV system's high costs are related to the high energy demand. An increased number of batteries is needed.
Solar dryer	Table A.38	Table A.39	Table A.40	Besides solar irradiation, this equipment uses an attached solar PV system to supply power to the electric fans and maintain the airflow inside the drying cabinet. Another type of solar dryer also employs solar thermal panels to heat the air in the attached cabinet.
Fish filleting machine	Table A.41	Table A.42	Table A.43	Overall, this is mechanized equipment and has a high energy demand, hence the high cost of the solar photovoltaic system.
Fish skinning machine	Table A.44	Table A.45	Table A.46	
Fish scaling machine	Table A.47	Table A.48	Table A.49	
Packaging vacuum sealer machine	Table A.50	Table A.51	Table A.52	
Can sealing machine	Table A.53	Table A.54	Table A.55	
Solar vending cart	Table A.56	Table A.57	Table A.58	The PV system is intended to provide energy for lighting, coolers or freezers integrated into the carts, and mobilization.
Gas motor engine		Table A.59		Data related to gas engine generators (running on biogas or biomethane) can also be used to supply energy to the units presented above.
Biodiesel motor engine		Table A.60		Data related to biodiesel or SVO that can also be used to supply energy to the units presented above.

Source: Authors' own elaboration.

8.1 FISHING LIGHTS AND LAMPS: CAPTURE/AQUACULTURE

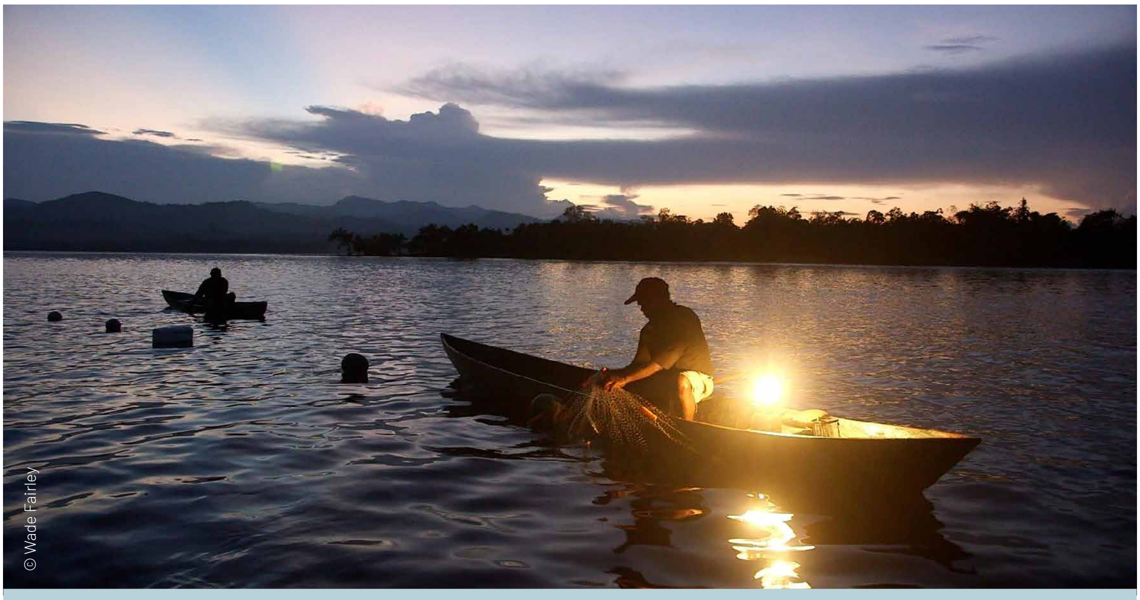
► TABLE A.5
Technology specifications and cost for solar lamps/fishing lights

SOLAR LANTERN/FISHING LIGHTS	
Lantern type	LED
Power[W]	1–50
Voltage [V]	5–12
Lamp luminous flux [lm]	200–4 800
Working time [h]	0.5–96
Battery	3.2–5V, 1 500–4 000mAh, Lithium-ion
Charging time [h]	6–10
Materials	ABS plastic, aluminium water and impact-resistant
Price [USD]	3.46–129[a]

[a] Batteries excluded.

Source: Authors' own elaboration.

► FIGURE A.3
Example of a fishing lamp



Source: Fairley, W. 2013. Lantern fishing, Solomon Islands. In: *Flickr.* Cited 22 April 2022. https://www.flickr.com/photos/theworldfishcenter/16523409123

► TABLE A.6

Technical specifications, investment and running cost for solar lamp/fishing lights photovoltaic systems

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	195
Max. power voltage (Vpm) [V]	21.4
Open circuit voltage (VoC) [V]	24.3
Module efficiency [%]	19.67
Cost [USD/unit]	145
Certifications	IEC 61215, UL 1703, IEC 61730, IEC 61701, IEC 62716 ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER DATA	
Capacity [kW]	0.4
Max voltage [V]	54
Power factor	0.99
Cost [USD/unit]	181
BATTERY DATA	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	12.8
Nominal capacity [Ah]	40
Cost [USD/unit]	590
Certifications	IEC 61427, CE, IEC 60896

Source: Authors' own elaboration.

▶ **TABLE A.7**

Investment and running cost for solar lamps/fishing lights photovoltaic systems

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	1 040	1 033	859	852
O&M costs [USD/kWh]	0.32	0.29	0.28	0.25

[a] AC system – Low irradiation: panels: 1, inverters: 1, batteries: 1.
[b] AC system – High irradiation: panels: 1, inverters: 1, batteries: 1.
[c] DC system – Low irradiation: panels: 1, batteries: 1.
[d] DC system – High irradiation: panels: 1, batteries: 1.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	352	345
O&M costs [USD/kWh]	0.17	0.14

[a] AC system – Low irradiation: panels: 1, inverters: 1.
[b] AC system – High irradiation: panels: 1, inverters: 1.

Source: Authors' own elaboration.

8.2 ELECTRIC BOAT MOTOR ENGINE: CAPTURE/AQUACULTURE

▶ **TABLE A.8**

Technology specifications and cost for electric boat motor engine

ELECTRIC BOAT MOTOR ENGINE FOR FISHING OR PROPULSION OF TRANSPORT BOATS	
Type	Outboard engines
Voltage [V]	DC 12–48, AC 100–240
Power [kW]	0.5–4
Controls	Tiller or single lever control, remote control, or tiller option
Maximum speed [km/h]	5–13
Shaft length [m]	0.6–1.15
Comparable HP [HP]	5 aprox.
Weight [kg]	2.45–18.3
Suggested batteries	98–125 Amps DC
Uses	Lakes, rivers, coast

(Cont.)

ELECTRIC BOAT MOTOR ENGINE FOR FISHING OR PROPULSION OF TRANSPORT BOATS	
Application	Electric boat with solar charged batteries
Price [USD]	108–3 999[a]

[a] Batteries excluded.

Source: Authors' own elaboration.

▶ FIGURE A.4
Example of a solar powered fishing boat

Source: Jebulon. 2011. Seafood fishing boat: Greece. In: *Wikicommons*. Cited 21 April 2022. https://commons.wikimedia.org/wiki/File:Seafood_fishing_boat_greece.jpg

▶ TABLE A.9
Technical specifications, investment and running cost for electric boat motor engine photovoltaic system

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	325
Max. power voltage (Vpm) [V]	33.5
Open circuit voltage (VoC) [V]	40.3
Module efficiency [%]	19.56
Minimum number of panels [modules]	120
Cost [USD/unit]	155
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716; ISO 9001: 2015, ISO 14001: 2015

(Cont.)

PV SYSTEM	
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	1.5
Max voltage [V]	60
Power factor	0.99
Number inverters	12
Cost [USD/unit]	375
BATTERY DATA	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	100
Number of batteries	28
Cost [USD/unit]	2 183
Certifications	IEC 61427, CE, IEC 60896

Source: Authors' own elaboration.

► TABLE A.10

Investment and running cost for electric boat motor engine photovoltaic systems
a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	97 837	63 357	93 337	61 857
O&M costs [USD/kWh]	0.13	0.16	0.13	0.16

[a] AC system – Low irradiation: panels: 120, inverters:12, batteries: 28.
[b] AC system – High irradiation: panels: 27, inverters: 4, batteries: 25.
[c] DC system – Low irradiation: panels: 120, batteries: 28.
[d] DC system – High irradiation: panels: 27, batteries: 25.

(Cont.)

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	36 515	8 684
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 120, inverters: 12.
[b] AC system – High irradiation: panels: 27, inverters: 4.

Source: Authors' own elaboration.

8.3 SOLAR AERATOR: CAPTURE/AQUACULTURE

► TABLE A.11

Technology specifications and cost for solar aerator

SOLAR AERATOR	
Type	Paddle wheel
Voltage [V]	48/220/380/440
Power [kW]	0.35–1.5
Impeller quantity	2–4
Material	Plastic water paddle wheel aerator
Oxygenation rate [kg/h]	>2.6
Covering area [m^2]	660–6 660
Certifications	ISO 9001, CE
Price [USD]	140–2 860

Source: Authors' own elaboration.

► FIGURE A.5

Example of an automatic aerator

Source: Layzell, C. 1980. Aerators in intensive shrimp pond – Lhokseumawe, Indonesia. In: *Flickr*. Cited 28 April 2022. https://www.flickr.com/photos/theworldfishcenter/42825216965

► TABLE A.12

Technical specifications, investment and running cost for solar aerator photovoltaic systems

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	325
Max. power voltage (Vpm) [V]	33.5
Open circuit voltage (VoC) [V]	40.3
Module efficiency [%]	19.56%
Cost [USD/unit]	155
Certifications	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716; ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	1.5
Max voltage [V]	60
Power factor	0.99
Cost [USD/unit]	375
BATTERY DATA	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	100
Cost [USD/unit]	2 183
Certifications	IEC 61427, CE, IEC 60896

Source: Authors' own elaboration.

► **TABLE A.13**

Investment and running cost for solar aerator photovoltaic systems

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	7 163	6 617	6 788	6 242
O&M costs [USD/kWh]	0.14	0.11	0.13	0.11

[a] AC system – Low irradiation: panels: 9, inverters: 1, batteries: 2.
[b] AC system – High irradiation: panels: 7, inverters: 1, batteries: 2.
[c] DC system – Low irradiation: panels: 9, batteries: 2.
[d] DC system – High irradiation: panels: 7, batteries: 2.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	2 699	2 153
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 9, inverters: 1.
[b] AC system – High irradiation: panels: 7, inverters: 1.

Source: Authors' own elaboration.

8.4 SOLAR AUTOMATIC FISH POND FEEDER: CAPTURE/AQUACULTURE

► **TABLE A.14**

Technology specifications and cost for solar automatic fish pond feeder

AUTOMATIC FISH POND FEEDER	
Feed box capacity [kg]	75–240
Voltage [V]	DC12/AC220-380
Power [W]	18–1 500
Endurance [h]	7–16
Throwing radius [m]	3–14
Weight [kg]	25–42
Speed [m/min]	20–23
Feeding way	Electromagnet drive
Material	Galvanized sheet, ABS Plastic
Application	Aquaculture, fish farming, fish pond
Price [USD]	120–1 500

Source: Authors' own elaboration.

► FIGURE A.6
Example of fish feeding

Source: Aytan Pixabay. 2016. In: *Pixabay*. Cited 28 April 2022. https://pixabay.com/cs/photos/urfa-fishygol-pstruh-ryba-ferm-1701676/

► TABLE A.15
Technical specifications, investment and running cost for solar automatic fish pond feeder photovoltaic systems

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	325
Max. power voltage (Vpm) [V]	33.5
Open circuit voltage (VoC) [V]	40.3
Module efficiency [%]:	19.56
Cost [USD/unit]	155
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716; ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	1.5
Max voltage [V]	60
Power factor	0.99
Cost [USD/unit]	375

(Cont.)

PV SYSTEM	
BATTERY	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	40
Cost [USD/unit]	959
Certifications	IEC 61427, CE, IEC 60896

Source: Authors' own elaboration.

▶ TABLE A.16

Investment and running cost for solar automatic fish pond feeder photovoltaic systems

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	6 157	5 808	5 782	5 436
O&M costs [USD/kWh]	0.14	0.11	0.13	0.11

[a] AC system – Low irradiation: panels: 7, inverters: 1, batteries: 4.
[b] AC system – High irradiation: panels: 6, inverters: 1, batteries: 4.
[c] DC system – Low irradiation: panels: 7, batteries: 4.
[d] DC system – High irradiation: panels: 6, batteries: 4.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	2 223	1 873
O&M costs [USD/kWh]	0.11	0.09

[a] AC system – Low irradiation: panels: 7, inverters: 1.
[b] AC system – High irradiation: panels: 6, inverters: 1.

Source: Authors' own elaboration.

8.5 SOLAR WATER PUMP: CAPTURE/AQUACULTURE

► TABLE A.17

Technology specifications and cost for solar water pump

SOLAR WATER PUMP	
Type	Water distribution, submersible
Flow rate [m³/h]	3.2–7
Max head [m]	6–100
Outlet diameter [mm]	12.7–50.8
Pressure	Low–high pressure
Power [W]	145–2 200
Voltage [V]	24/48/96/220/280
Cable length [m]	1.2–3
Certifications	CE, ISO, SGS
Material	Stainless steel 304
Price [USD]	106–530

Source: Authors' own elaboration.

► FIGURE A.7

Example of a solar water pump

Source: IWMI/Schmitter, P. 2015. A farmer in Lemo with his newly installed solar pump. In: *Flickr*. Cited 28 April 2022. https://www.flickr.com/photos/africa-rising/34754722623

► TABLE A.18

Technical specifications, investment and running cost for solar water pump photovoltaic system

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	325
Max. power voltage (Vpm) [V]	33.5
Open circuit voltage (VoC) [V]	40.3
Module efficiency [%]	19.56
Cost [USD/unit]	155
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716; ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	0.4
Max voltage [V]	54
Power factor	0.99
Cost [USD/unit]	181
BATTERY DATA	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	40
Cost [USD/unit]	1000
Certifications	IEC 61427, CE, IEC 60896

Source: Authors' own elaboration.

► TABLE A.19

Investment and running cost for solar water pump photovoltaic system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	9 705	8 941	8 981	8 217
O&M costs [USD/kWh]	0.14	0.11	0.14	0.11

[a] AC system – Low irradiation: panels: 11, inverters: 4, batteries: 6.
[b] AC system – High irradiation: panels: 8, inverters: 4, batteries: 6.
[c] DC system – Low irradiation: panels: 11, batteries: 6.
[d] DC system – High irradiation: panels: 8, batteries: 6.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	3 607	2 843
O&M costs [USD/kWh]	0.11	0.09

[a] AC system – Low irradiation: panels: 11, inverters: 4.
[b] AC system – High irradiation: panels: 8, inverters: 4.

Source: Authors' own elaboration.

8.6 ICE MAKING MACHINE: STORAGE AND PROCESSING

► TABLE A.20

Technology specifications and cost for ice making machines

ICE MAKING MACHINE			
Type	Automatic		
Cooling way	Air cooling – water cooling		
ICE SHAPE	FLAKE	CUBE	BLOCK
Capacity [kg/day]	500–8 000	180–900	50–6 000
Refrigerant	R404a/R22a	R22/R404a/R134a	R22/R404a
Voltage [V]	110/220/380/440	220	220/380
Power [W]	1 500–33 000 W	1400–2224 W	4 200–22 000 W
Weight [kg]	103–1 670 Kg	98–205 Kg	200–1 200 Kg
Price [USD]	2 425–27 000	799–3 128	2 000–80 000

Source: Authors' own elaboration.

► **FIGURE A.8**

Example of an ice maker machine

Source: Sek, M. 2011. Laboratory icemaker. In: *Commons Wikimedia.* Cited 22 April 2022. https://commons.wikimedia.org/wiki/File:Laboratory_icemaker.jpg

► **TABLE A.21**

Technical specifications, investment and running cost for ice making machines photvoltaic system

PV SYSTEM	ICE FLAKE MAKING MACHINE	ICE CUBE MAKING MACHINE	ICE BLOCK MAKING MACHINE
PV PANELS			
Type	Mono	Mono	Mono
Nominal maximal power (Pmax) [W]	330	325	325
Max. power voltage (Vpm) [V]	33.8	33.5	33.5
Open circuit voltage (VoC) [V]	40.6	40.3	40.3
Module efficiency [%]	19.4	19.56	19.56
Cost [USD/unit]	157	155	155
Certifications:	IEC 61215, UL 1703, IEC 61730, ISO 9001: 2015, ISO 14001: 2015; IEC61701, IEC62716		
MPPT			
Max. off-load-voltage of PV system [Vdc]	75	75	75
Nominal voltage	10	10	10
Cost [USD/unit]	98	98	98

(Cont.)

PV SYSTEM	ICE FLAKE MAKING MACHINE	ICE CUBE MAKING MACHINE	ICE BLOCK MAKING MACHINE
Inverter			
Capacity [kW]	1.5	1.5	1.5
Max voltage [V]	60	60	60
Power factor	0.99	0.99	0.99
Cost [USD/unit]	375	375	375
BATTERY			
Type	Lithium	Lithium	Lithium
Battery losses	15%	15%	15%
Depth of discharge for battery	40%	40%	40%
Nominal voltage [V]	25.6	25.6	25.6
Nominal capacity [Ah]	100	100	100
Cost [USD/unit]	2 183	2 138	2 138
Certifications	IEC 61427, CE, IEC 60896		

Source: Authors' own elaboration.

► TABLE A.22

Investment and running cost for flake ice making machines photovoltaic system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	123 138	112 779	117 513	107 154
O&M costs [USD/kWh]	0.13	0.11	0.13	0.11

[a] AC system – Low irradiation: panels: 151, inverters: 15, batteries: 35.
[b] AC system – High irradiation: panels: 113, inverters: 15, batteries: 35.
[c] DC system – Low irradiation: panels: 151, batteries: 35.
[d] DC system – High irradiation: panels: 113, batteries: 35.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	46 635	36 276
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 151, inverters: 15.
[b] AC system – High irradiation: panels: 113, inverters: 15.

Source: Authors' own elaboration.

► TABLE A.23

Investment and running cost for cube ice making machines photovoltaic system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/IINVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	14 036	12 799	13 286	12 049
O&M costs [USD/kWh]	0.14	0.11	0.13	0.11

[a] AC system – Low irradiation: panels: 17, inverters: 2, batteries: 4.
[b] AC system – High irradiation: panels: 12, inverters: 2, batteries: 4.
[c] DC system – Low irradiation: panels: 17, batteries: 4.
[d] DC system – High irradiation: panels: 12, batteries: 4.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	5 206	3 969
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 17, inverters: 2
[b] AC system – High irradiation: panels: 12, inverters: 2.

Source: Authors' own elaboration.

► TABLE A.24

Investment and running cost for block ice making machines photovoltaic system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	94 683	86 846	90 183	82 346
O&M costs [USD/kWh]	0.13	0.11	0.11	0.08

[a] AC system – Low irradiation: panels: 116, inverters: 12, batteries: 27.
[b] AC system – High irradiation: panels: 87, inverters: 12, batteries: 27.
[c] DC system – Low irradiation: panels: 116, batteries: 27.
[d] DC system – High irradiation: panels: 87, batteries: 27.

(Cont.)

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	35 644	27 807
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 116, inverters: 12.
[b] AC system – High irradiation: panels: 87, inverters: 12.

Source: Authors' own elaboration.

8.7 PORTABLE FREEZER: PROCESSING, MARKETING AND DISTRIBUTION

► TABLE A.25
Technology specifications and cost for solar portable freezer

CHEST, HORIZONTAL, DEEP FREEZER	
Capacity [L]	20–90
Refrigerant	R134a
Temperature for freezer [°C]	−18 to +5 −18 to +10
Power [W]	32–50
Voltage [V]	DC12/24/230, AC 110V/120V
Weight [kg]	15–32
Ambient range [°C]	+10 to +45
Defrost	Manual
Certifications	UL
Price [USD]	280–961

Source: Authors' own elaboration.

▶ **FIGURE A.9**

Example of a solar portable cooler/freezer

Source: Ridgway, S. 2011. In: *Flickr.* Cited 22 April 2022. https://www.flickr.com/photos/stephanridgway/5388987683/in/photolist-pto6hj-pdVqyY-2imcsCd-VouvDi-bAXRAt-2n3FEjf-9dcYhK-9dg6sY-9dd1yP-9dg75m-pvo8ab-4U1fmf-2n1uAgd-2mztvc2-2mzuGZq-264XJtR

▶ **TABLE A.26**

Technical specifications, investment and running cost for solar portable freezer photovoltaic system

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	195
Max. power voltage (Vpm) [V]	21.4
Open circuit voltage (VoC) [V]	24.3
Module efficiency [%]	19.67
Cost [USD/unit]	145
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716 ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	0.4
Max voltage [V]	54
Power factor	0.99
Cost [USD/unit]	181

(Cont.)

PV SYSTEM	
BATTERY DATA	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	20
Cost [USD/unit]	580
Certifications	IEC 61427, CE, IEC 60896

Source: Authors' own elaboration.

► TABLE A.27

Investment and running cost for solar portable freezer photovoltaic system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	1 066	1 052	884	871
O&M costs [USD/kWh]	0.19	0.16	0.17	0.14

[a] AC system – Low irradiation: panels: 1, inverters: 1, batteries: 1.
[b] AC system – High irradiation: panels: 1, inverters: 1, batteries: 1.
[c] DC system – Low irradiation: panels: 1, batteries: 1.
[d] DC system – High irradiation: panels: 1, batteries: 1.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	387	374
O&M costs [USD/kWh]	0.13	0.10

[a] AC system – Low irradiation: panels: 1, inverters: 1.
[b] AC system – High irradiation: panels: 1, inverters: 1.

Source: Authors' own elaboration.

8.8 SOLAR COLD STOREROOM: STORAGE, PROCESSING, MARKETING AND DISTRIBUTION

► TABLE A.28

Technology specifications and cost for solar cold storeroom

SOLAR COLD/FREEZER ROOM	
Voltage [V]	208/220/380/400/420/440
Power [kW]	0.85–80
Temperature [°C]	−60 to +20 −45 to +20
Cooling capacity [Tonne]	3–100
Cooling way	Air cooling, water cooling
Refrigerant	R-22, R-404a, R-407, R-408, R-507, R134a
Door type:	Swing/sliding/truck door
Material	Steel/stainless steel – polyurethane insulation board
Room panels thickness [mm]	100, 75, 50
Certification	CE/ISO 9 001
Price [USD]	15 000–30 000

Source: Authors' own elaboration.

► FIGURE A.10

Example of a solar cold storeroom

Source: Tatlow, A. 2017. Asfordby C Solar Farm control gear container. In: *Geograph*. Cited 22 April 2022. https://www.geograph.org.uk/photo/5925165

► TABLE A.29

Technical specifications, investment and running cost for solar cold storeroom photovoltaic system

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	330
Max. power voltage (Vpm) [V]	33.8
Open circuit voltage (VoC) [V]	40.6
Module efficiency [%]	19.4
Cost [USD/unit]	157
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716; ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	1.5
Max voltage [V]	60
Power factor	0.99
Cost [USD/unit]	375
BATTERY	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	100
Cost [USD/unit]	2 183
Certifications	IEC 61427, CE, IEC 60896

Source: Authors' own elaboration.

▶ **TABLE A.30**

Investment and running cost for solar cold storeroom photovoltaic system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	1 925 504	1 852 389	1 912 004	1 838 889
O&M costs [USD/kWh]	0.18	0.15	0.18	0.15

[a] AC system – Low irradiation: panels: 1 058, inverters: 36, batteries: 744.
[b] AC system – High irradiation: panels: 789, inverters: 36, batteries: 744.
[c] DC system – Low irradiation: panels: 1 058, batteries: 744.
[d] DC system – High irradiation: panels: 789, batteries: 744.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	301 254	228 139
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 1 058, inverters: 36.
[b] AC system – High irradiation: panels: 789, inverters: 36.

Source: Authors' own elaboration.

8.9 FISH SMOKER KILNS: PROCESSING

▶ **TABLE A.31**

Technology specifications and cost for fish smoker kilns

FISH SMOKER			
Smoking system	Metal drum	Chorkor	FTT
Type of construction	Rudimentary	Improved	Based on existing kiln models while addressing their shortcomings
Smoking time	Up to 3 days	1 day	3–6 hours
Smoking technique	Simultaneous smoking and drying	Separate smoking and drying	Separate smoking and drying
Smoking capacity [kg fish /day]	150–200	200–300	3 000
Equivalent of wood needed [kg wood/kg fish]	3–5	> 0.8	0.8
Energy required [MJ/kg fish]	48–80	>12.8	12.8

(Cont.)

FISH SMOKER			
Equivalent of charcoal needed [kg charcoal/kg fish]	1.55–2.59	>0.41	0.41
Equivalent of pellets needed [kg pellets/kg fish]	3.6–7.1	> 1.1	0.1
Lifespan	2 years	3–15 years	> 15 years
Fuel source	Wood/charcoal/pellets	Wood/charcoal/pellets	Wood/charcoal/pellets
Automatic grade	Semi-automatic	Semi-automatic	Semi-automatic
Cost of kiln [USD]	26	345	1 600

Source: Mindjimba, K. 2020. *Study on the profitability of fish smoking with FTT-Thiaroye kilns in Côte D'ivoire.* FAO Fisheries and Aquaculture Circular No. 1155. Rome, FAO. www.fao.org/3/ca8220en/CA8220EN.pdf

► FIGURE A.11
Example of a fish smoker

Source: Burgess, A. 2020. Arbroath Smokies Haddock. In: *Commons Wikimedia.* Cited 22 April 2022. https://commons.wikimedia.org/wiki/File:Arbroath_Smokies_-_geograph.org.uk_-_481678.jpg

8.10 FISH ELECTRIC SMOKER: PROCESSING

► TABLE A.32
Technology specifications and cost for electric fish smoker

ELECTRIC FISH SMOKER	
Type	Electric
Capacity [kg/h]	30–1 000
Power [kW]	2.75–30
Voltage [V]	220/380
Steam pressure [MPa]	0.1–0.2

(Cont.)

ELECTRIC FISH SMOKER	
Automatic grade	Semi-automatic
Certifications	CE, ISO, TUV
Price [USD]	856–8 280

Source: Authors' own elaboration.

► TABLE A.33

Technical specifications, investment and running cost for electric fish smoker photovoltaic system

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	425
Max. power voltage (Vpm) [V]	41.4
Open circuit voltage (VoC) [V]	49.1
Module efficiency [%]	19.8
Cost [USD/unit]	252
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716; ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	1.5
Max voltage [V]	60
Power factor	0.99
Cost [USD/unit]	375
BATTERY	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	100
Cost [USD/unit]	2 183
Certifications	IEC 61427, CE, IEC 60896

Source: Authors' own elaboration.

► TABLE A.34

Investment and running cost for electric smoker photovoltaic system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	107 047	113 163	102 172	107 538
O&M costs [USD/kWh]	0.13	0.11	0.13	0.11

[a] AC system – Low irradiation: panels: 97, inverters: 13, batteries: 29.
[b] AC system – High irradiation: panels: 83, inverters: 15, batteries: 34.
[c] DC system – Low irradiation: panels: 97, batteries: 29.
[d] DC system – High irradiation: panels: 83, batteries: 34.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	43 642	38 843
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 97, inverters: 13.
[b] AC system – High irradiation: panels: 83, inverters: 15.

Source: Authors' own elaboration.

8.11 ELECTRIC DRYING MACHINE: PROCESSING

► TABLE A.35

Technology specifications and cost for electric dryer

DRYING MACHINE	
Capacity [kg/batch]	20–3 500
Power [kW]	0.45–28
Voltage [V]	220/380
Rated current [A]	5–30
Working temperature [°C]	≤ 180
Dehydration amount [L/h]	3.5–40
Material	304 stainless steel
Refrigerant gas	R134a
Humidity control [%]	5–99
Trays	12–192
Weight [kg]	65–1 500

(Cont.)

DRYING MACHINE	
Certifications	CCC CE ISO
Price [USD]	490–30 000

Source: Authors' own elaboration.

► FIGURE A.12
Example of an electric dryer

Source: Yatherm. 2014. Hot air oven. In: *Commons Wikimedia*. Cited 22 April 2022. https://commons.wikimedia.org/wiki/File:Hot_air_oven_.jpg

► TABLE A.36
Technical specifications, investment and running cost for electric dryer photovoltaic system

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	425
Max. power voltage (Vpm) [V]	41.4
Open circuit voltage (VoC) [V]	49.1
Module efficiency [%]	19.8
Cost [USD/unit]	252
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716 ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	1.5
Max voltage [V]	60
Power factor	0.99
Cost [USD/unit]	375

(Cont.)

PV SYSTEM	
BATTERY	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	100
Cost [USD/unit]	2 183
Certifications	IEC 61427, CE, IEC 60896

Source: Authors' own elaboration.

► TABLE A.37

Investment and running cost for electric dryer photovoltaic system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	107 047	97 111	102 172	92 236
O&M costs [USD/kWh]	0.13	0.11	0.13	0.11

[a] AC system – Low irradiation: panels: 97, inverters: 13, batteries: 29.
[b] AC system – High irradiation: panels: 83, inverters: 15, batteries: 34.
[c] DC system – Low irradiation: panels: 97, batteries: 29.
[d] DC system – High irradiation: panels: 83, batteries: 34.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	43 642	33 706
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 97, inverters: 13.
[b] AC system – High irradiation: panels: 83, inverters: 15.

Source: Authors' own elaboration.

8.12 SOLAR DRYER: PROCESSING

► TABLE A.38
Technology specifications and cost for solar dryer

SOLAR FISH DRYER	
Capacity [kg]	20–800
Power [W]	3–3 500
Voltage [V]	12/220
Operating temperature [°C]	45–85
Automatic grade	Semi-automatic, automatic
Weight [kg]	200–800
Certifications	CE, ISO
Materials	Stainless steel 304, iron or poly carbonate, aluminium
Price [USD]	203–6 500

Source: Authors' own elaboration.

► FIGURE A.13
Example of a solar dryer

Source: Young Stuart, M. 2012. Solar lumber kiln. In: *Flickr*. Cited 28 April 2022. https://www.flickr.com/photos/melystu/8217083616

► TABLE A.39
Technical specifications, investment and running cost for solar dryer photovoltaic system

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	425
Max. power voltage (Vpm) [V]	41.4
Open circuit voltage (VoC) [V]	49.1
Module efficiency [%]	19.8

(Cont.)

PV SYSTEM	
PV PANELS	
Cost [USD/unit]	252
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716; ISO 9001: 2015 ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/ unit]	98
INVERTER	
Capacity [kW]	0.4–1.5
Max voltage [V]	54–60
Power factor	0.99
Cost [USD/unit]	181
BATTERY DATA	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	12.8
Nominal capacity [Ah]	80
Cost [USD/unit]	959
Certifications	IEC 61427, CE, IEC 60896

Source: Authors' own elaboration.

▶ TABLE A.40

Investment and running cost for solar dryer photovoltaic system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	14 603	12 753	13 517	12 003
O&M costs [USD/kWh]	0.14	0.11	0.14	0.11

[a] AC system – Low irradiation: panels: 12, inverters: 6, batteries: 9.
[b] AC system – High irradiation: panels: 12, inverters: 2, batteries: 4.
[c] DC system – Low irradiation: panels: 12, batteries: 9.
[d] DC system – High irradiation: panels: 12, batteries: 4.

(Cont.)

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	5 874	3 923
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 12, inverters: 6.
[b] AC system – High irradiation: panels: 12, inverters: 2.

Source: Authors' own elaboration.

8.13 FISH FILLETING MACHINE: PROCESSING

► TABLE A.41
Technology specifications and cost for fish filleting machines

FISH FILLETING MACHINE	
Capacity [kg/h, pcs/min]	180–1 000, 20–70
Voltage [V]	110/220/380
Power [kW]	1–7
Material	304 Stainless Steel
Weight [kg]	50–390
Function	Cutting, bone removing, filleting Optional: slaughtering, scaling, gutting, cutting and cleaning
Automatic grade	Manual, automatic
Certifications	CE, SGS, ISO
Price [USD]	200–8 500

Source: Authors' own elaboration.

► FIGURE A.14
Example of fish fillets

Source: Verch, M. 2020. Raw frozen tilapia fillet background. In: *Flickr*. Cited 22 April 2022. www.flickr.com/photos/30478819@N08/50216948292/in/photostream

► TABLE A.42

Technical specifications, investment and running cost for fish filleting machines photovoltaic system

PV SYSTEM	
PV panels	
Type	Mono
Nominal maximal power (Pmax) [W]	325
Max. power voltage (Vpm) [V]	33.5
Open circuit voltage (VoC) [V]	40.3
Module efficiency [%]	19.56
Cost [USD/unit]	155
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716 ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	1.5
Max voltage [V]	60
Power factor	0.99
Cost [USD/unit]	375
BATTERY	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	100
Cost [USD/unit]	2 183
Certifications	IEC 61427, CE, IEC 60896

Source: Authors' own elaboration.

► **TABLE A.43**

Investment and running cost for fish filleting machines photovoltaic system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	30 844	28 429	29 344	26 929
O&M costs [USD/kWh]	0.14	0.11	0.13	0.11

[a] AC system – Low irradiation: panels: 36, inverters: 4, batteries: 9.
[b] AC system – High irradiation: panels: 27, inverters: 4, batteries: 9.
[c] DC system - Low irradiation: panels: 36, batteries: 9.
[d] DC system – High irradiation: panels: 27, batteries: 9.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	11 099	8 639
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 36, inverters: 4.
[b] AC system – High irradiation: panels: 27, inverters: 4.

Source: Authors' own elaboration.

8.14 FISH SKINNING MACHINE: PROCESSING

► **TABLE A.44**

Technology specifications and cost for fish skinning machines

FISH SKINNING MACHINE	
Capacity [pcs/min, kg/h]	15–50 pcs/min, 180–2 000 Kg/h
Voltage [V]	110/220/380
Power [kW]	0.2–1.5
Material	304 stainless steel
Weight [kg]	48–173
Function	Fish skin removing/peeling
Automatic grade	Semi-automatic, automatic
Certifications	CE, TUV, ISO
Price [USD]	900–10 000

Source: Authors' own elaboration.

► FIGURE A.15
Example of a skinned fish

Source: Verch, M. 2020. Cleaned raw fish on a white kitchen board. In: *Flickr*. Cited 22 April 2022. https://www.flickr.com/photos/30478819@N08/48558172377/in/photolist-2gYVjUz-2gAyLoy-2hNSJ86-2hNSHR9-2gAzjYp-2k8iqEc-2gkicWR-2cK9bAp-2gvjfrh-2gGVAvW-2i6JKJ5-2jvuZcj-2jZDuVe-2fKwoYU-2jZcqkz-2jZHZ3n-2jqAcwd-2ki1iSx-2dwwS4x-2kopxN3-2jvuZYe-2gGUQQi-2kQJJRQ-2eQKe5N-2jZDv4R-2f99ATE-2eVktNH-2fQ84dg-SLABYQ-2gxCGyq-SLABpy-2hpscq6-2hcG4Dw-2khW5ZT-2gxCGs8-SLACn5-2jFGP8x-2jPrCC2-2k9ta6R-2k9xpYC-2jFFWzh-2kQK8gn-2jPvbCw-2kwVRMA-TFSnLm-2i6aBER-2k9wZUK-2i68GTn-2gxCGiR-2hpKvow

► TABLE A.45
Technical specifications, investment and running cost for fish skinning machines photovoltaic system

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	325
Max. power voltage (Vpm) [V]	33.5
Open circuit voltage (VoC) [V]	40.3
Module efficiency [%]	19.56
Cost [USD/unit]	155
Certifications	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716 ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	1.5
Max voltage [V]	60
Power factor	0.99
Cost [USD/unit]	375

(Cont.)

PV SYSTEM	
BATTERY	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	100
Cost [USD/unit]	2 183

Source: Authors' own elaboration.

► TABLE A.46

Investment and running cost for fish skinning machines photovoltaic system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	6 933	6 406	6 558	6 031
O&M costs [USD/kWh]	0.14	0.11	0.14	0.11

[a] AC system – Low irradiation: panels: 8, inverters: 1, batteries: 2.
[b] AC system – High irradiation: panels: 6, inverters: 1, batteries: 2.
[c] DC system – Low irradiation: panels: 8, batteries: 2.
[d] DC system – High irradiation: panels: 6, batteries: 2.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	2 469	1 942
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 8, inverters: 1.
[b] AC system – High irradiation: panels: 6, inverters: 1.

Source: Authors' own elaboration.

8.15 FISH SCALING MACHINE: PROCESSING

► TABLE A.47
Technology specifications and cost for fish scaling machines

FISH SCALE REMOVING MACHINE	
Capacity [pcs/min, kg/h]	30–60, 180–500
Production capacity [%]	98–99
Voltage [V]	110/220/380
Power [kW]	0.7–7
Material	304 Stainless Steel
Weight [kg]	80–390
Function	Fish slaughtering /Gutting/Scaling
Automatic grade	Semi-automatic, Automatic
Certifications	CE, ISO
Price [USD]	500–12 000

Source: Authors' own elaboration.

► FIGURE A.16
Example of fish scaling

Source: Cohn, A. 2016. Scaling Fish, Indonesia. In: Flickr. Cited 18 November 2022. https://live.staticflickr.com/8209/28709409093_74dc8482f0_b.jpg

► TABLE A.48
Technical specifications, investment and running cost for fish scaling machines photovoltaic system

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	330

(Cont.)

PV SYSTEM	
PV PANELS	
Max. power voltage (Vpm) [V]	33.8
Open circuit voltage (VoC) [V]	40.6
Module efficiency [%]	19.4
Cost [USD/unit]	157
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716; ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	1.5
Max voltage [V]	60
Power factor	0.99
Cost [USD/unit]	375
BATTERY	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	100
Cost [USD/unit]	2 183

Source: Authors' own elaboration.

▶ TABLE A.49

Investment and running cost for fish scaling machines photovoltaic system
a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	28 262	26 025	26 762	24 525
O&M costs [USD/kWh]	0.13	0.11	0.13	0.11

[a] AC system – Low irradiation: panels: 34, inverters: 4, batteries: 8.
[b] AC system – High irradiation: panels: 26, inverters: 4, batteries: 8.
[c] DC system – Low irradiation: panels: 34, batteries: 8.
[d] DC system – High irradiation: panels: 26, batteries: 8.

(Cont.)

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	10 700	8 463
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 34, inverters: 4.
[b] AC system – High irradiation: panels: 26, inverters: 4.

Source: Authors' own elaboration.

8.16 PACKAGING VACUUM SEALER MACHINE: PROCESSING

► TABLE A.50

Technology specifications and cost for vacuum sealer machines

VACUUM SEALER MACHINE	
Vacuum limit [MPa]	0.0002–0.8
Pump motor power [kW]	0.5–9
Sealing power [kW]	0.18–1
Voltage [V]	110/220/380
Sealing length [mm]	220–1 100
Sealing width [mm]	4–100
Displacement chamber [m³/h]	20–300
Chamber type	Single, double
Material	Stainless steel 304
Packaging type/material	Bags, pouch, film, trays, case/plastic
Packing speed [cycles/minute]	2–6
Weight [kg]	50–700
Certifications	CE/ROHS, ISO 9001, ISO 14001
Price [USD]	200–18 000

Source: Authors' own elaboration.

► **FIGURE A.17**

Example of a vacuum sealer machine

© J. Wallingford

Source: Wallingford, J. 2013. XtraVac double chamber vacuum packaging machine. In: *Commons Wikimedia.* Cited 22 April 2022. https://en.m.wikipedia.org/wiki/File:XtraVac_Double_Chamber_Vacuum_Packaging_Machine.png

► **TABLE 51**

Technical specifications, investment and running cost for vacuum sealing machines photovoltaic systems

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	325
Max. power voltage (Vpm) [V]	33.5
Open circuit voltage (VoC) [V]	40.3
Module efficiency [%]	19.56
Cost [USD/unit]	125
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716 ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	1.5
Max voltage [V]	60
Power factor	0.99
Cost [USD/unit]	375
BATTERY	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%

(Cont.)

PV SYSTEM	
BATTERY	
Nominal voltage [V]	25.6
Nominal capacity [Ah]	100
Cost [USD/unit]	2 183

Source: Authors' own elaboration.

► TABLE A.52

Investment and running cost for vacuum sealing machines photovoltaic system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	38 792	35 570	36 917	33 695
O&M costs [USD/kWh]	0.13	0.11	0.13	0.11

[a] AC system – Low irradiation: panels: 48, inverters: 5, batteries: 11.
[b] AC system – High irradiation: panels: 36, inverters: 5, batteries: 11.
[c] DC system – Low irradiation: panels: 48, batteries: 11.
[d] DC system – High irradiation: panels: 36, batteries: 11.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	14 681	11 428
O&M costs [USD/kWh]	0.11	0.08

[a] AC system – Low irradiation: panels: 48, inverters: 5.
[b] AC system – High irradiation: panels: 36, inverters: 5.

Source: Authors' own elaboration.

8.17 CAN SEALING MACHINE: PROCESSING

► TABLE A.53

Technology specifications and cost for can sealing machines

CAN SEALING MACHINE	
Power [kW]	0.37–2.1
Voltage [V]	380/220/110
Tank high [mm]	25–300
Sealing diameter[mm]	30–153
Sealing max speed [(Pcs, can, bottles)/min]	30–60
Operation	Automatic, semi-automatic
Driven type	Electric
Material	304 stainless Steel, carbon steel (spray lacquer)
Weight [kg]	40–350
Price [USD]	402–8 000

Source: Authors' own elaboration.

► FIGURE A.18

Example of a can sealing machine

Source: Dei Fratelli. 2018. Can sealing. In: *Commons Wikimedia*. Cited 22 April 2022. https://commons.wikimedia.org/wiki/File:Can_Sealing.jpg

► FIGURE A.19

Example of canned fish

Source: Verch, M. 2019. Open canned sardines fish on the table. In: *Flickr*. Cited 22 April 2022. https://www.flickr.com/photos/30478819@N08/48272021032/in/photolist-2jx2LXH-2gxCirH-2gxCGs8-2gxCGyq-2gw8zX8-2gxCJqS-2gxCJep-2hcG4Dw-2gxCGT3-2gxCGiR-2gxCJ5G-2gxCJkG-2m5naQi-2jBPFsg-2jBPFmj-2jBPFhM-2jF5QxU-2jBLdhn-2keW94j-2keSjkg-2keWzFx

► TABLE A.54

Technical specifications, investment and running cost for can sealing machines photovoltaic system

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	325
Max. power voltage (Vpm) [V]	33.5
Open circuit voltage (VoC) [V]	40.3
Module efficiency [%]	19.56
Cost [USD/unit]	155
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716; ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	1.5
Max voltaje [V]	60
Power factor	0.99
Cost [USD/unit]	375

(Cont.)

PV SYSTEM	
BATTERY	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	100
Cost [USD/unit]	2 183

Source: Authors' own elaboration.

► TABLE A.55

Investment and running cost for can sealing machines PV system
a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	10 343	9 718	9 593	8 968
O&M costs [USD/kWh]	0.14	0.11	0.14	0.11

[a] AC system – Low irradiation: panels: 11, inverters: 2, batteries: 3.
[b] AC system – High irradiation: panels: 9, inverters: 2, batteries: 3.
[c] DC system – Low irradiation: panels: 11, batteries: 3.
[d] DC system – High irradiation: panels: 9, batteries: 3.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	3 696	3 071
O&M costs [USD/kWh]	0.11	0.09

[a] AC system – Low irradiation: panels: 11, inverters: 2.
[b] AC system – High irradiation: panels: 9, inverters: 2.

Source: Authors' own elaboration.

8.18 SOLAR VENDING CART: DISTRIBUTION/MARKETING

► TABLE A.56

Technology specifications and cost for solar vending cart/bike/motorbike with chest freezer

SOLAR VENDING CART	
Voltage [V]	12/24/36
Distance [km]	60–80
Average speed [km/h]	25
Battery	Gel, lithium 12–60v, 10–100 Ah
Front wheel size	2–3 wheels, 0.508 m
Loan capacity [kg]	50–200
Freezer type	Chest/deep Freezer
Power consumption [W]	70–1 000
Voltage [V]	12/24–220/110
Capacity [L]	95–208
Temperature [°C]	−13 to −30
Refrigerant	R600a/R134a
Defrost	Manual
Door	Single, folding
Price [USD]	222–2 700[a]

[a] Batteries excluded.

Source: Authors' own elaboration.

► FIGURE A.20

Example of a solar vending cart with chest cooler/freezer

Source: Freecold. 2021. Solar Powered Refrigerator and Freezers. In: Freecold. Cited 21 April 2022. www.freecold.com/en/freecold-photovoltaic-solar-refrigeration/refrigerators-freezers/

▶ **TABLE A.57**

Technical specifications, investment and running cost for solar vending cart photovoltaic system

PV SYSTEM	
PV PANELS	
Type	Mono
Nominal maximal power (Pmax) [W]	325
Max. power voltage (Vpm) [V]	33.5
Open circuit voltage (VoC) [V]	40.3
Module efficiency [%]	19.56
Cost [USD/unit]	155
Certifications:	IEC 61215, UL 1703, IEC 61730, IEC61701, IEC62716; ISO 9001: 2015, ISO 14001: 2015
MPPT	
Max. off-load-voltage of PV system [Vdc]	75
Nominal voltage	10
Cost [USD/unit]	98
INVERTER	
Capacity [kW]	0.74
Max voltage [V]	54
Power factor	0.99
Cost [USD/unit]	302
BATTERY	
Type	Lithium
Battery losses	15%
Depth of discharge for battery	40%
Nominal voltage [V]	25.6
Nominal capacity [Ah]	40
Cost [USD/unit]	1 000

Source: Authors' own elaboration.

► TABLE A.58

Investment and running cost for solar vending cart photovoltaic system

a) Off-grid

	AC SYSTEM/INVERTER INCLUDED		DC SYSTEM/INVERTER EXCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]	LOW IRRADIATION[c]	HIGH IRRADIATION[d]
Total capital cost [USD]	4 713	4 421	4 411	4 119
O&M costs [USD/kWh]	0.14	0.12	0.14	0.12

[a] AC system – Low irradiation: panels: 5, inverters: 1, batteries: 3.
[b] AC system – High irradiation: panels: 4, inverters: 1, batteries: 3.
[c] DC system – Low irradiation: panels: 5, batteries: 3.
[d] DC system – High irradiation: panels: 4, batteries: 3.

b) On-grid

	AC SYSTEM/INVERTER INCLUDED	
	LOW IRRADIATION[a]	HIGH IRRADIATION[b]
Total capital cost [USD]	1 615	1 323
O&M costs [USD/kWh]	0.11	0.09

[a] AC system – Low irradiation: panels: 11, inverters: 2.
[b] AC system – High irradiation: panels: 9, inverters: 2.

Source: Authors' own elaboration.

8.19 GAS MOTOR ENGINE

► TABLE A.59

Technology specifications and cost for gas motor engine

NATURAL GAS/BIOGAS/NG/LPG CLEAN ENERGY	
Power [kW]	4.85–180
Max output	7.5HP/ 1500–4000rpm
Bore x stroke[mm]	68 to 116.5*54 to 148
Starting system	recoil/electric starting
Oil capacity [L]	0.6
Stroke	4
Cold Style:	Air cooled/water cooled
Displacement:	0.22–9.5
Cylinder	6
Fuel tank capacity [L]	3.6–4.2
Ignition system	Transistored ignition
Fuel Consumption [g/kWh]	340
Certification:	ISO, CE

(Cont.)

NATURAL GAS/BIOGAS/NG/LPG CLEAN ENERGY	
Weight [kg]	16–750
Price [USD]	80–12 500

Source: Authors' own elaboration.

▶ **FIGURE A.21**

Example of a biogas motor engine

Source: RCEE. 2009. Biogenerator1. In: *Flickr*. Cited 28 April 2022. https://flic.kr/p/6GJ9c1

8.20 BIODIESEL MOTOR ENGINE

▶ **TABLE A.60**

Technology specifications and cost for bio-oil motor engine

SVO MOTOR ENGINE	
Power [MW]	1–2
Frequency [Hz]	50–60
Diameter x strokes [mm]	158.8–270 x 158.8–385
Cylinders	5–8
Rotation [rpm]	750–1500
Cont. power rate [KWe]	1 000–2 241
Fuel consumption [L/h]	166–569
Fuel density [Kg/L]	0.85
Fuel consumption [L/KWe]	0.222–0.2621
Fuel consumption [L/KWe/1MW/2MW]	223–517
Genset number	*1–2
Biofuel heat rate [MJ/Kg]	37.5

(Cont.)

SVO MOTOR ENGINE	
Biofuel density [Kg/L]	0.91
Fuel consumption [L/KWe/Bio-oil]	0.2787–0.2348
Elec. price [USD/KWh]	0.2208
Oil price (Yen/Kg)	0.69

Source: Authors' own elaboration.

THE SMALL-SCALE FISHERIES AND ENERGY NEXUS
OPPORTUNITIES FOR RENEWABLE ENERGY INTERVENTIONS

Renewable sources of energy are gaining traction worldwide. Solar, wind power, biomass energy and geothermal heat energy are already used in applications in food value chains. Renewable energy can provide energy solutions in situations where there are challenges with traditional energy supplies. Renewable energy also has the capacity to reduce the carbon footprint of food value chains and help mitigate against climate change. Yet, the link between renewable energy and small-scale fisheries and aquaculture is not well documented.

This publication introduces the current situation and proposes a way forward with regard to the use of renewable energy in small-scale fisheries. It provides general guidance for decision-makers and development specialists on the choices, benefits and challenges related to renewable energy use and uptake in small-scale fisheries. The publication will contribute to the implementation of the FAO Code of Conduct for Responsible Fisheries (CCRF) and the FAO Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Alleviation (SSF Guidelines). FAO's objectives relate to better production, better nutrition and better environment.

Fisheries and Aquaculture Division –
Natural Resources and Sustainable Production
Fi-Inquiries@fao.org
fao.org/fisheries

Food and Agriculture Organization of the United Nations
Rome, Italy

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