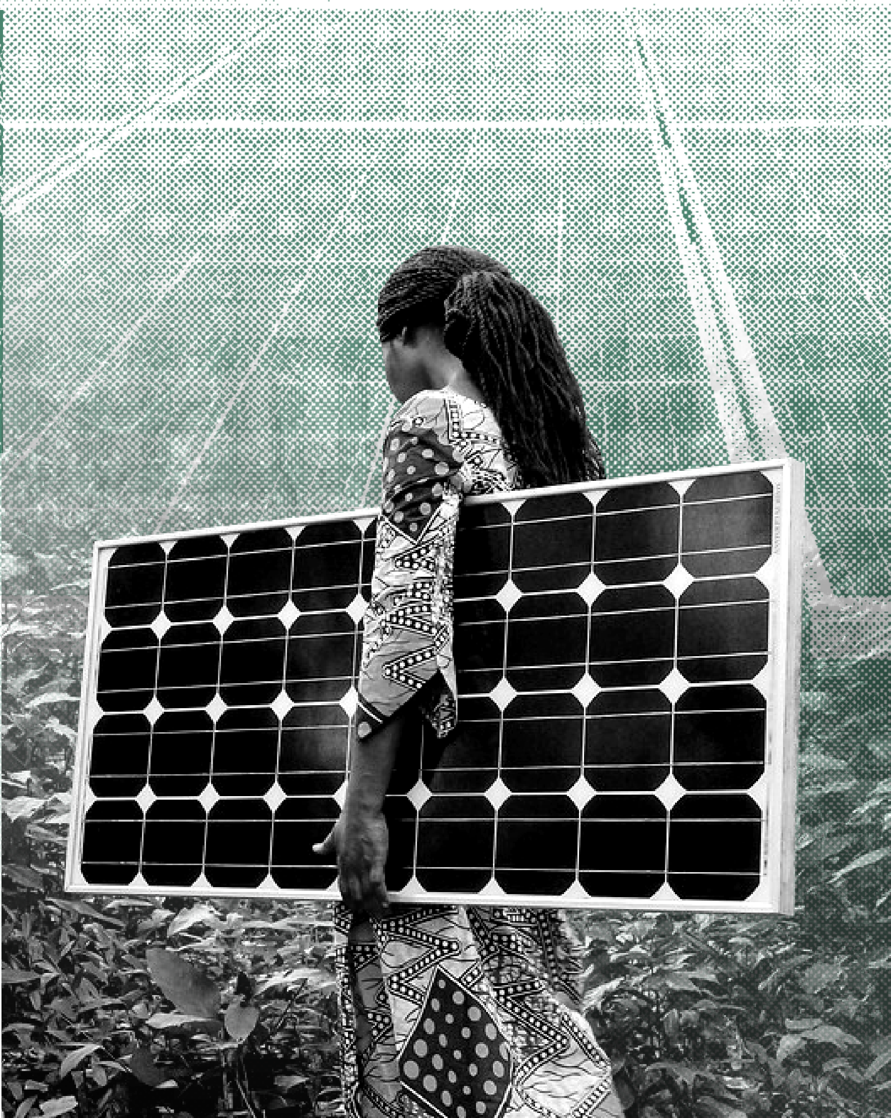
Food and Agriculture Organization of the United Nations

RENEWABLE ENERGY FOR AGRI-FOOD CHAINS

INVESTING IN SOLAR ENERGY IN RWANDA



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Number 2

RENEWABLE ENERGY FOR AGRI-FOOD CHAINS
INVESTING IN SOLAR ENERGY IN RWANDA

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Food and Agriculture Organization of the United Nations
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Foreword

Our agri-food systems face the challenge of having to feed a rising global population, improve people's health and nutrition, create decent jobs, raise incomes and reduce global greenhouse gas (GHG) emissions. To reach these objectives, agri-food systems will need to undertake significant investments to become more sustainable, efficient and energy smart.

The adoption of clean and renewable energy technologies along agri-food value chains can help minimize emissions, improve productivity and competitiveness and make better use of the earth's natural resources. It can also help countries meet their international development commitments, including under the Nationally Determined Contributions (NDCs) and 2030 Sustainable Development Agenda. Countries seeking to meet their growing food and energy needs while simultaneously reducing their carbon footprint are looking at ways to increase investments in renewable energy sources such as solar, wind and hydropower to lessen their dependence on fossil fuels.

This new knowledge product looks specifically at existing opportunities for the uptake of solar energy technologies in Rwanda's agri-food chains. Developing a modern agro-processing industry requires reliable access to affordable electricity to run the processing equipment and cold storage needed to produce higher value products and reduce losses. Solar energy could help Rwanda upgrade its agri-food chains and render them competitive. This assessment identifies the energy requirements at each stage of the agro-processing chain, showing the market potential and areas that hold the most promise.

Understanding the overall market size of specific technologies allows governments to develop policies and identify public investments that can hasten the deployment of such technologies. It also provides the private sector with information on opportunities for investing in renewable energy. The methodology used in this assessment could in future be applied to other options in the broad range of renewable energy technologies for the agri-food sector.

We are grateful to all who contributed to the assessment. We remain committed to helping countries find and invest in alternative green energy solutions while improving their energy efficiency and increasing their use of renewables for more sustainable agri-food systems.

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Abbreviations and acronyms

CPV	unit cost of Unit of electricity generated with a solar PV system (USD/kW)
CWS	coffee washing stations
Ed	unit of electricity required to process one Unit of product (kWh/tonnes)
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GDP	gross domestic product
GHG	greenhouse gas
HHP	high growth of production
HMP	high market penetration
LGP	low growth of production
LMP	low market penetration
MCCs	modern collection centers
MINAGRI	Ministry of Agriculture
MMP	medium market penetration
MPR	market penetration rate
Pe	unit price of the identified piece of equipment (USD)
PV	photovoltaic
Qe	processing capacity of an individual piece of equipment (tonnes/yr)
Qp	total processed quantity by crop (tonnes/yr)
RNDP	Rwanda National Dairy Platform
SDGs	Sustainable Development Goals
UHT	ultra-high temperature processing

Executive summary

Sustainable and efficient agri-food systems depend on stable access to energy, from farm to plate. But for many developing countries across the world, limited access to energy hinders the growth of modern agri-food systems, prevents farmers from producing higher value products and results in food losses. Countries are faced with either having to pursue fossil fuels for development, contributing further to climate change, or leapfrogging to more sustainable and renewable sources of energy.

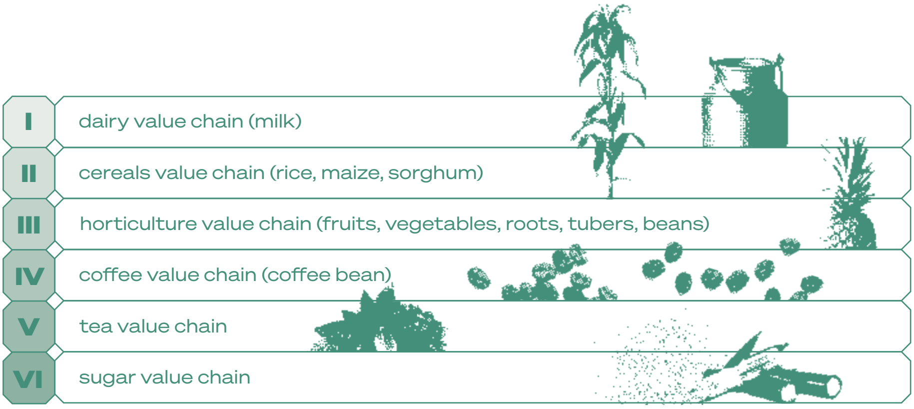
The Food and Agriculture Organization of the United Nations (FAO), through the Energy Smart Food programme, has been spearheading efforts to support countries in building evidence-based policies and deploying renewable energy technologies in the agri-food sector. Improving access to renewables helps countries address Sustainable Development Goal 7 – access to affordable and clean energy – as well as their NDC pledges.

In Rwanda, agriculture accounts for around one-third of the country's gross domestic product (GDP) and employs about 70 percent of the working population. The sector continues to gain momentum towards achieving its full potential, but agro-processing is still limited. Developing a modern agro-processing industry hinges on the availability of and access to reliable and affordable electricity.

Rwanda is committed to achieving energy access for all by 2024. The adoption of solar technologies has become a national priority and represents a unique opportunity for the country's agriculture sector. Solar-powered equipment such as cold storage, milling, drying and other technologies could enable the transition to less fossil fuel-intensive agricultural production systems. However, this requires a clear understanding of viable solar energy solutions, taking into consideration the specific context and needs of the country. Defining which solar energy solutions are feasible will also allow the private sector to get involved, thus enabling a market-led scaling up of these technologies.

Using a methodological approach, this report provides a broad estimate of existing opportunities for the uptake of solar energy technologies within Rwanda's agri-food chains. As a first step, the assessment identified the country's agri-food chains, breaking them down into their main production and processing blocks. It identified the energy requirements required at each stage of the agro-processing chain. Results, presented by agri-food value chain groups, include a baseline analysis and sensitivity analysis to market penetration and growth in production.

Rwanda's crops and commodities were grouped into the following value chains:



Solar energy interventions were classified into two groups – Type 1 and Type 2. Type 1 includes decentralized solar equipment catering to a specific stage of the value chain, while Type 2 represents opportunities in which electricity demand could be substituted by solar-based photovoltaic (PV) systems.

The analysis highlighted the areas with significant theoretical market potential and possible first entry points for solar-based interventions in the country. Understanding the overall market size of specific technologies could allow the Government to develop policies that hasten the deployment of these technologies and help the private sector target specific opportunities.

The assessment found that Type 1 solar energy interventions in the horticulture, milk and cereal value chains were especially promising. Estimates suggest that the potential market size for specific solar technologies in the horticulture chain could reach around USD 470 million. The potential market size for small-scale milk chillers in Rwanda could reach USD 25 million. In the rice value chain, solar-based equipment could reach a total market potential of more than USD 20 million, while in the maize and sorghum value chain, the potential market size for solar technologies is around USD 40 million. Should these technologies be deployed, they could solve some of the structural constraints to modernizing the country's agribusiness sector and have a larger social impact by creating job opportunities and new business developments.

It is important to note that while the focus of this assessment was specifically on identifying solar energy technologies in Rwanda and estimating their market potential, the methodology could also be applied to other renewable energy technologies. Solar energy is one option available within a broad range of renewable energy technologies. Therefore, solar energy solutions should be screened against other renewable energy alternatives to find the most sustainable and cost-effective energy solutions for the agri-food chain.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Chapter 1
Introduction

Access to energy is essential in order to ensure sustainable and efficient agri-food systems and food security. It is a key input into the agri-food chain for enabling the use of modern practices and equipment on farming, in addition to storing, processing and ultimately, the consumption of food. In several developing economies in Africa, agriculture continues to play a central role both in terms of contribution to the country's income as well as the provision of jobs and livelihood. In fact, growth and development channelled through this sector has been found to be twice as effective in targeting poverty reduction as compared to other sectors. Nevertheless, energy access and its use are still limiting factors that hinder the growth of a sustainable agri-food system. Given the lack of access to energy and the need to find alternative climate friendly energy solutions, developing countries are faced with a choice between: (i) pursuing development-based fossil fuels, thus further contributing to climate change, or; (ii) leapfrogging to more sustainable and renewable sources of energy, which can support economic development that is also environmentally sustainable. These efforts are mirrored in Goal 7 of the Sustainable Development Goals (SDGs) and in countries' pledges recorded in the Nationally Determined Contributions (NDC). Alternative energy sources and the related technologies can play a key role in diversifying away from fossil fuels in a way that reduces or mitigates GHG emissions. Identifying which technologies and renewable energy sources can be used at each stage of the value chain represents the first step in this process.

Energy access in Rwanda is still limited, however the country is committed to achieving energy access for all by 2030. Rwanda is a landlocked country in east Africa where agriculture is an important sector of the economy. The agriculture sector contributes around one-third of the country's GDP and employs approximately 70 percent of the working population. Agriculture is practised extensively and in addition to producing cereals, fruits and vegetables, the country has a growing livestock and fisheries sector. Bananas, sweet potatoes and cassava were the most produced crop by production volumes in 2017, each with a total volume of more than 1 million tonnes per year. Milk production reached 250 000 tonnes in 2017, the majority of which

was cow milk while a smaller share was from sheep and goats. Nonetheless, a major bottleneck within the agriculture sector is the lack of modern food processing and storage technologies that can be used to produce higher value products, as well as reduce losses by providing cold storages. In fact, development of a modern agro-processing industry depends on the availability and access to reliable and affordable electricity required to run processing equipment and cold storage.

Access to a stable supply of electricity is however still limited, although there has been significant progress in the last 10 years. In 2018, around 51 percent of households had access to electricity, 37 percent of which were connected to the national grid and 14 percent connected through decentralised electricity systems. The target is to have 100 percent electricity access by 2024, with 52 percent of households connected through grid extension and 48 percent connected through decentralised off-grid technologies.

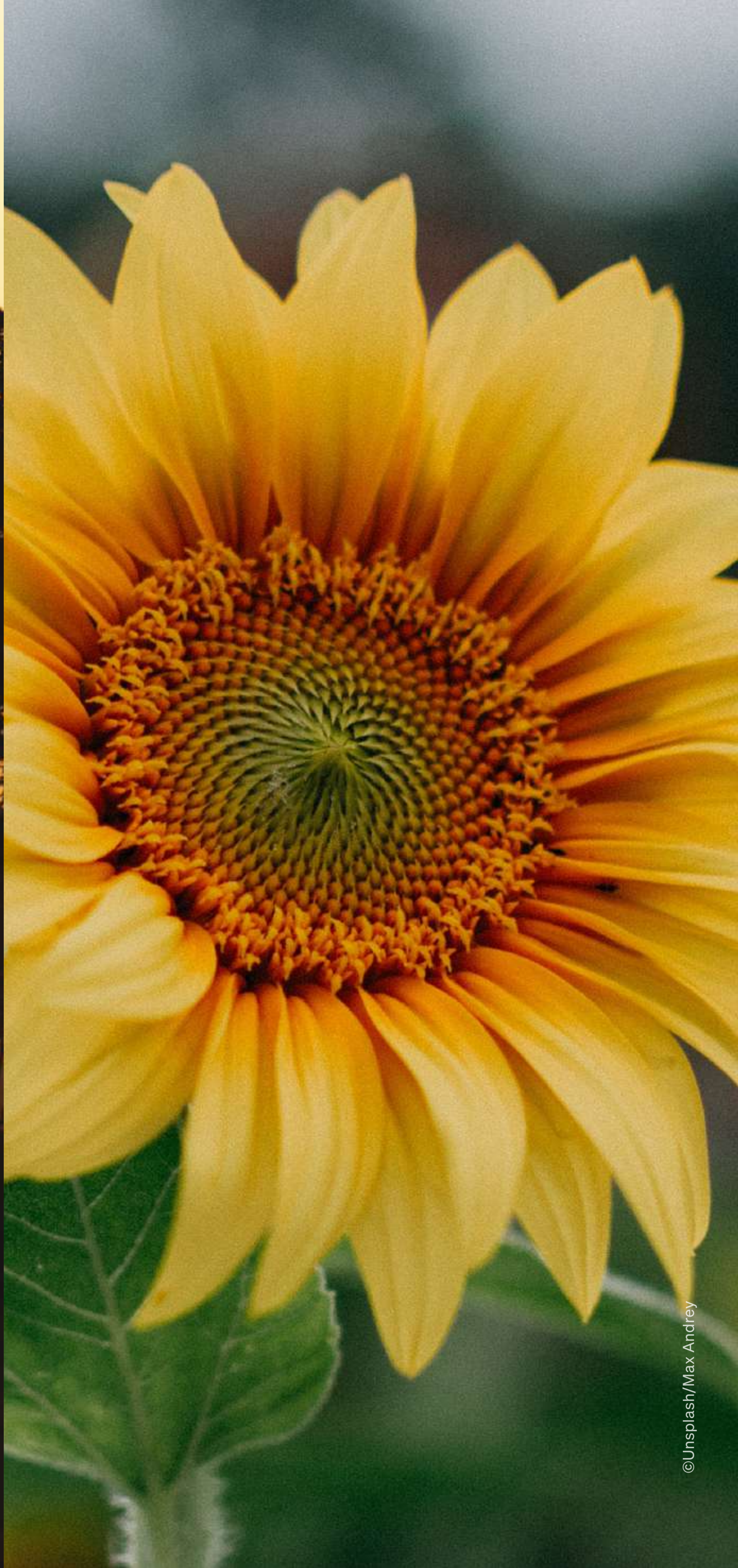
The agriculture sector in Rwanda continues to gain momentum towards achieving its full potential but agro-processing is still limited. Rwanda's agro-processing industrial masterplan (KPMG, 2014) reports that while more than half of Rwanda's exports are comprised of agriculture-based industrial products, less than 30 percent of those exports are in fact, processed goods (this can be compared to 98 percent in the developed world). One channel through which value chains could be further developed in Rwanda is the enhancement of agri-businesses (processing, cold storage, drying) access to affordable sources of electricity. Therefore, finding energy alternatives that include and target agriculture can in fact contribute to the development of the agri-food sector as well as the energy sector in Rwanda. Solar-powered equipment, such as solar cold storage, milling, drying and other technologies are some of the solutions that might enable the transition to a less fossil fuel-intensive agricultural production system. However, this requires fully understanding which solar energy solutions could be viable, while taking into consideration the specific context and needs of the country. Defining which solar energy solutions are feasible will also allow for the involvement of the private sector thus enabling a market-led scaling up of these technologies.

Rwanda is located approximately two degrees below the equator and as a consequence has significant potential to produce solar energy[1]. Solar energy could be a key engine for upgrading agricultural value chains in the country, especially given the currently favourable environment policy. Rwanda aims to reach universal energy access by 2024. This is especially relevant to the 48 percent of the electricity access that is expected to be provided by off-grid sources. The adoption of solar technologies has become a national priority and represents a unique opportunity for the agriculture sector.

1 The country receives solar irradiance of approximately 5kWh/m2/day and peak sun hours of approximately 5 hours per day. Solar irradiation is the amount of electromagnetic radiation received from the sun per unit area (usually square meters). This is generally used as a measure to estimate how much PV electricity can be produced in the area.

This report provides an initially broad estimate of the existing opportunities for the uptake of solar energy technologies and increased access to energy within the agri-food chains in Rwanda. The aim of this report is to assess the market potential for solar energy in agri-food chains in Rwanda and therefore focuses solely on solar energy. This said, the results should be viewed in a wider context and while considering energy access options for agri-food chains, solar energy solutions should be screened against other energy alternatives.

As a first step, the assessment identifies the main agri-food chains in the country and breaks down the chains into their main production and processing blocks. Within each stage of the agro-processing chain the energy requirements are identified. Results are then presented by an agri-food chain group, including a baseline analysis and sensitivity analysis to market penetration and growth in production.



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Chapter 2
Methodology

To estimate the market potential for solar energy within agri-food chains in Rwanda, the first required step is to define which agri-food chains are currently in place in Rwanda. These agri-food chains have been reviewed based on the stages of the agri-food chains and the opportunities for solar energy uptake within each stage. The sections below begin by outlining the agri-food chain groups in Rwanda and are followed by defining the analytical steps of the market potential assessment.

2.1. AGRI-FOOD CHAINS IN RWANDA

The first step in the analysis is to identify the specific agri-food chains currently operational in Rwanda and where and at what stage of the chain solar energy can be used.

Following the initial production stage, each crop or agricultural commodity goes through several steps before it reaches the final stage where it is consumed. These interlined processes that are involved in bringing an agricultural product from production to final consumption, with value addition at each stage is called a value chain. Broadly speaking, the food value chain consists of 5 main steps: production, aggregation and storage, processing, marketing and distribution and consumption. While these 5 stages are commonly found in all crops and agricultural commodities, the processes within each stage of the value chain can vary significantly. Many of these processes are very specific to the commodity or crop being analysed and vary across value chains. As a result, the energy demand is crop, commodity and value chain specific, and the energy required and technology option at each stage can be very different. In the end, the resulting energy demand levels can be very different for each value chain (see Figure 1).

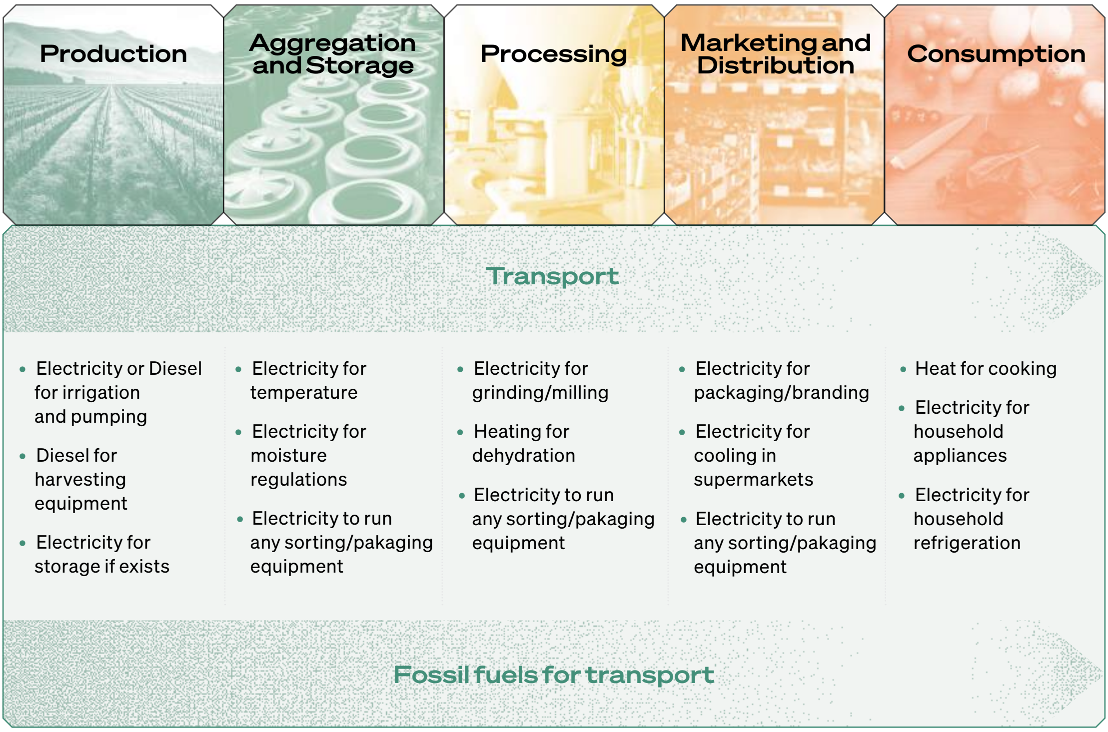


Figure 1
A typical food value chain with examples of energy use at each step

SOURCE: Diagram by the authors.

A range of agricultural products, which include crops, livestock and crop and livestock are produced in Rwanda. Given this wide range of agricultural products, the agricultural commodities were reviewed in terms of volumes of production, complexity of the chains and energy requirements at each stage of the value chain. Because of this, the crops and products that undergo similar processes were grouped together and those with minimal energy requirements and opportunities were discarded, given that the market in these cases would be too narrow.

In terms of crops production, Table 1 lists the top crops produced in Rwanda in 2017. As shown, these include a variety of cereals, fruit, vegetables and roots and tubers.

Table 1

Crop production in Rwanda in 2017

Crop item	Production Quantity (tonnes)	Area harvested (ha)	Yield (hg/ha)
Bananas	1 729 150	464 862	37 197
Sweet potatoes	1 078 973	184 609	58 446
Cassava	1 041 986	120 000	86 832
Potatoes	846 184	93 991	90 028
Beans, dry	455 822	549 441	8296
Maize	358 417	297 447	12 050
Pumpkins, squash and gourds	290 134	56 941	50 954
Taro (cocoyam)	215 015	55 463	38 767
Sorghum	151 447	143 490	10 555
Rice, paddy	108 958	31 583	34 499
Sugar cane	107 877	6906	156 201
Tomatoes	97 426	11 329	85 997
Cabbages and other brassicas	94 924	7436	127 655
Yams	50 000	6000	83 333
Tea	25 931	16 889	15 353
Soybeans	23 934	53 361	4485
Groundnuts, with shell	20 703	45 512	4549
Eggplants (aubergines)	20 000	6000	33 333
Pineapples	19 236	2382	80 756
Coffee, green	17 824	39 309	4534

SOURCE: FAOSTAT, 2019.

The most highly produced crops are bananas, sweet potatoes and cassava, in terms of volume. These crops are followed by potatoes, beans, maize, pumpkins, taro, sorghum, rice and sugar cane with volumes between 100 000 tonnes and 1 million tonnes. A range of other fruits, vegetables, tea, and coffee are produced with production volumes below 100 000 tonnes.

Fruits, vegetables, roots and tubers, and beans are highly perishable crops, therefore the value chains are characterised by the need to store them in a cool environment to avoid biological spoilage. In addition, while technically beans are legumes, when harvested fresh they also need to be stored in a cool environment to avoid biological spoilage. Furthermore, while all of these crops can be processed into other products, such a processing capacity is

limited in Rwanda and most of the produce is sold fresh. In fact, few processed products are currently produced in Rwanda, except for juices (mainly from pineapple and passion fruit with 2.05 million litres per year) (EU, 2014). Juices, mainly pineapple juice, comprise 92.8 percent of production of the total processed fruits and vegetables cooperatives in the country (MINAGRI and NAEB, 2014). Similarly, for roots and tubers, a very limited processing capacity exists and it is primarily found in potato chips production (2 factories) and cassava leaves drying. Therefore, given the lack of the processing capacity and a similarity in the value chains, as well as the need for vegetables, fruits, roots and tubers and beans to be cooled after harvesting, these crops were grouped into one group for the analysis and called the horticulture group.

Rice, maize and sorghum are other major crops produced in the country. These three crops are technically classified as cereals and go through similar processes in their respective value chains. Milling is a fundamental and characteristic part of the processing stage for rice, maize and sorghum. Therefore, rice, maize and sorghum were placed in one group for the analysis and called the cereals group.

Coffee is a major export crop in Rwanda and has a very distinct value chain comprised of drying, washing and finally the grinding of coffee beans. No other crop in Rwanda requires a process similar to that of coffee. As a result, coffee was kept separate and not grouped with other crops and was analysed as a separate value chain. This value chain was called the coffee value chain.

Tea is also a major export crop in Rwanda with a relatively small value chain consisting of growing the tea leaf and then transporting it to the tea processing factories from where it is exported. Tea value chain was not grouped with other commodities and was analysed as a separate value chain.

Sugar in Rwanda is produced mainly from sugar cane. Rwanda has only one sugar factory that produces around 13 percent of the domestic sugar consumption and the remaining is imported. Sugarcane is the primary feedstock used to produce sugar at the Kabuye sugar works which is already connected to the grid (Habes, 2017). Sugar value chain is small which consists of sugar cane producers supplying sugar cane to kabuye sugar works that produces crystalline sugar. Given that there is only on factory that produced sugar and that the process of making sugar differs greatly from other value chains, the sugar value chain was not grouped with any other commodity and analysed separately.

In terms of animal products, Rwanda's livestock sector is mainly comprised of cattle, goats, sheep, chickens and pigs (see Figure 2). The main livestock products produced in the country are milk, eggs, and meat, however, relatively little information was found on the eggs and meat sector in Rwanda and how it is currently organised. Milk production on the other hand is well documented, and the government has a plan dedicated to cattle development in place called "Girinka", which aims to provide one cow per family. In addition, milk is a unique commodity whose value chain is distinct from all other products. Once milk is produced, it needs to be stored and cooled down to 4oC to prevent pathogen growth. No other crop or commodity requires this level of cooling within such a short time span. As a result, milk was considered as an independent value chain and designated as "dairy value chain". Given the size of the markets, data availability and the policies in place, only milk was analysed.

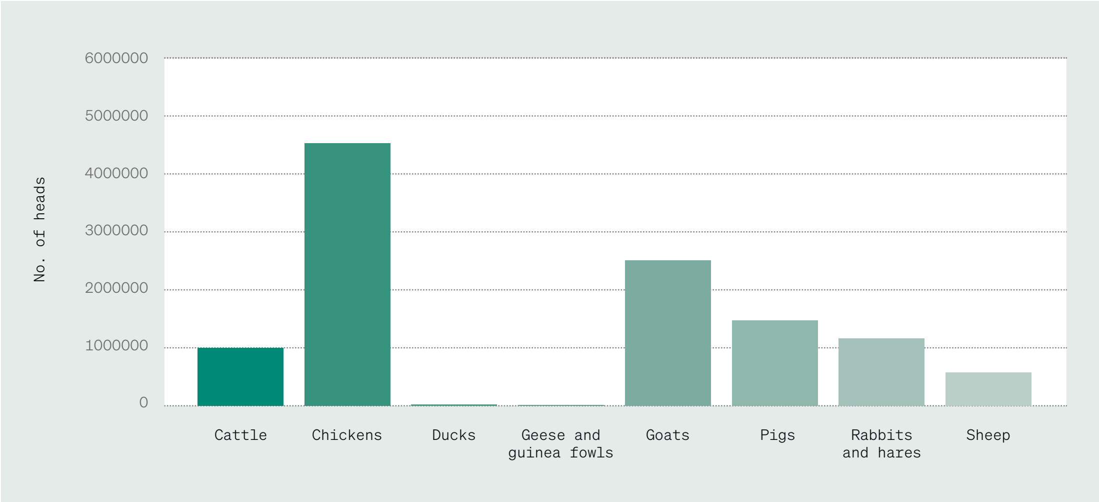


Figure 2
Livestock production 2017

SOURCE: FAOSTAT, 2019.

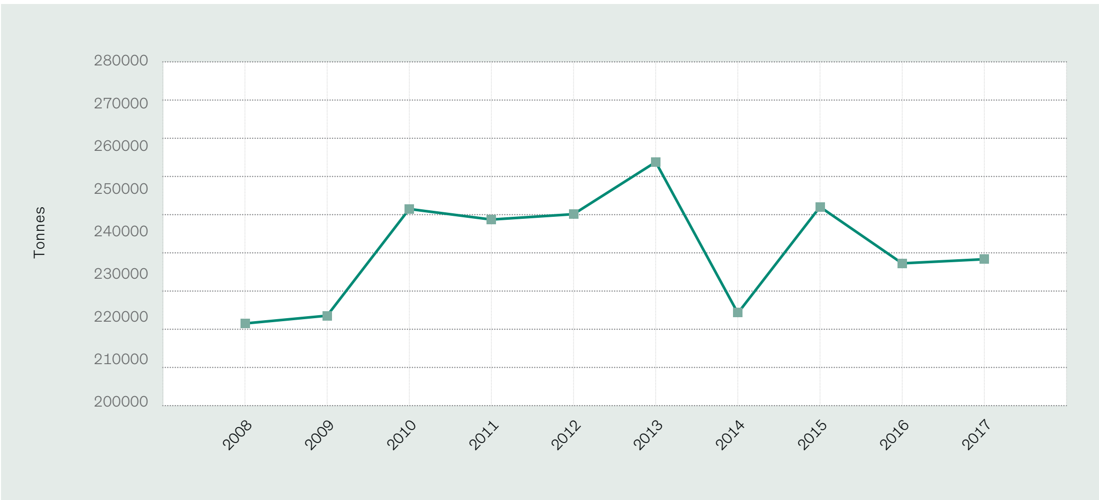
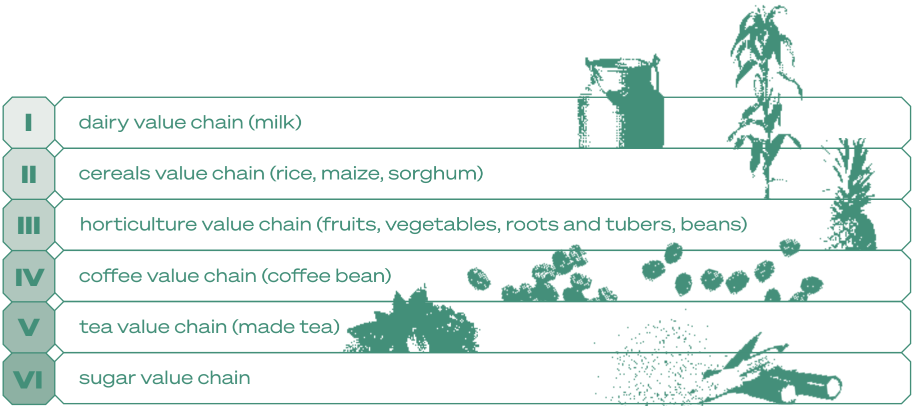


Figure 3
Total milk production 2008-2017

SOURCE: FAOSTAT, 2019.

Each value chain is broken up into the applicable stages of the selected value chain and the requirements for solar powered equipment and electricity are defined for each step of the chain, including the identification of the applicable technology for each step and type of chain.

In sum, given the range of agricultural products produced in the country, the stages of each value chain group, the possibilities for solar energy use and update, the various crops and commodities produced were grouped into the following six value chains and analysed by chain group:



2.2. SELECTION OF SOLAR TECHNOLOGIES AND ESTIMATION OF MARKET POTENTIAL

The market potential is defined as the entire size of the market for a specified product at a specific time[2] (Kotler *et al.*, 2001). As a result, this represents the upper limit of the market for the selected product and is generally reported by the sales value in a specified currency or by sales volume. In this report the market potential is reported by sales value in USD. In terms of solar energy, it can have two specific applications in agri-food systems resulting in two district market outlets, more specifically:

- **Type 1** solar powered equipment for productive uses at specific stages of the agri-food chain;
- **Type 2** solar PV systems to provide electricity at specific stages of the agri-food chain.

For Type 1 we consider all cases in which solar-powered equipment can be used within agri-food chains such as for example, solar powered cold storages, solar power milling machines. For Type 2 we consider the options for the processing stages of the value chain for which electricity can be supplied through solar PV systems.

The markets for Type 1 and Type 2 will be analysed for the agri-food chains groups as defined above. The total solar energy demand estimation for each chain is then tied to specific targets that the country has for that value chain. To illustrate this, we use an example taken from the horticulture value chain. In the case of the horticulture value chain, Rwanda has set a target to export approximately 50 000 tonnes of horticulture products by 2024 (MINAGRI, 2018). Horticulture products are highly perishable and

2 The estimation of market potential is a measure of the potential demand of a product or a service and as such does not include a cost benefit analysis or other measure of financial viability.

therefore need adequate cold storage systems. The cold storage is required to store the products given the export standards that these products need to adhere to for export. Therefore, for the horticulture value chain cold storage is an essential element of the chain, and solar energy could be an option to power these systems. Similar targets have been identified for each one of the value chain groups, including the components of the value chain and the applicable technologies. The details of the calculations are presented below for the two identified solar energy options for agri-food chains.

Type 1 Market size for solar powered equipment for productive uses in agri-food chain

The market size for solar powered solar equipment is calculated as follows:

$$\text{Market size}_1 = \left(\frac{Qp}{Qe}\right) * (pe) * (MPR)$$

- Market size: the market size of the solar powered equipment
- Qp: the total processed quantity by crop (tonnes/year). This quantity is based on the country specific targets as outlined in the specific sections by value chain type
- Qe: the processing capacity of an individual piece of equipment (tonnes/year)
- pe: the unit price of the identified piece of equipment (USD)
- MPR: Market Penetration Rate, initially assumed to be 1 (equivalent to 100 percent market penetration)

Type 2 Market size for solar PV systems for electricity supply

In addition to having specific solar powered equipment, much of the existing equipment can be powered by simply installing solar PV panels to produce electricity, as opposed to running them on grid electricity. This is analysed in the second case of this assessment. In this case, the results estimate the market potential of using solar PV systems to generate electricity in selected processing plants such as medium- to large-scale cereal milling factories or medium- to large-scale juice production facilities. Two different unit costs were used for PV electricity systems: low electricity generation capacity and a high electricity generation capacity. These values fall within the range of 1 000–3 500 USD/kW reported (Belyakov, 2019)[3]. Indeed, through field work done in Rwanda in 2019, the unit cost of solar PV electricity was found to be USD 1 767/kW for large scale PV systems and USD 2 273 /kW for small scale PV systems. This method was not exhaustive, but it allowed to account the economies of scales in in PV electricity generation. The market size for Type 2 is calculated as follows:

3 Market penetration rate is the share of the total market size that is supplied by a product or service. Market penetration and market adoption rates represent the same concept and will be used interchangeably in the discussion.

the unit of electricity required to process one unit of product (kWh/tonnes)

Market Penetration Rate, initially assumed to be 1 (equivalent to 100 percent market penetration)

$$\text{Market size}_2 = (Qp)*(Ed)*(Cpv)*(MPR)$$

the total amount processed final product (tonnes/year)

is the unit cost of unit of electricity generated with a solar PV system (USD/kW)

More details on the specific assumption for each value chain such as the quantities processed ranges and adoption rates are provided in the following chapters.

2.3. STRUCTURE OF ANALYSIS

2.3.1 Current production, production targets and solar based interventions

The first step in the analysis is to describe current production of the selected value chain in the country and, with reference to this outline, the target production volume. With respect to their policies the government has set out a series of targets for each value chain grouping or for products within the value chain grouping. These are considered within the analysis. Each value chain is then broken down into the components of the value chain and the relevant solar based interventions are qualified.

2.3.2 Full market potential (total addressable market size)

Considering the target production rates and the identified solar interventions, the analysis estimates that total addressable market size for both Type 1 and Type 2 interventions. The addressable market or full market potential defines the total market demand for a product or service if the market penetration rate is 100 percent (CFI, 2019).

2.3.3 Scenario analysis: market penetration and production growth rates and sensitivity analysis

The market penetration rate and the growth in production volumes are two central parameters influencing the estimation of the market potential. Given this, and departing from current production volumes, variations in production growth rates and market penetration rates are considered.

In terms of market penetration rates, three levels of market penetration are considered in the scenario analysis (see Table 2). The first is a low market penetration rate of 5 percent based on (Grimm *et al.*, 2016). This rate is based on the current adoption rates witnessed in Rwanda to date for solar lighting equipment and is used as a reference of solar powered equipment for agriculture use. The second is a medium penetration rate of 50 percent. This reflects an average adoption rate and half of the full market potential. The third is a high market penetration rate of 75 percent. This market penetration rate is based on the (Batidzirai, Moyo and Kapembwa, 2018).

Table 2
Market penetration rates

Market penetration	Rate (%)	Background assumption
Low market penetration (LMP)	5	Assumption based the average growth of PV systems on households in Rwanda*
Medium market penetration (MMP)	50	Average value
High market penetration (HMP)	75	Based on high potential willingness to pay of industrial consumers in a similar context**
Total addressable market size	100%	This is the market size if 100 % of the target market adopts a certain technology

SOURCE: Elaboration by the authors based on* (Grimm *et al.*, 2016), **(Batidzirai, Moyo and Kapembwa, 2018).

The market penetration rate is combined with the feasibility of potential growth in the agribusiness sector. The annual growth rates analyzed are included in Table 3. A low and a high annual production growth rate are considered in the sensitivity analysis. The low annual production growth rate is assumed to be up to 2.5 percent and is based on the fact that between 2017 and 2018, this was the rate of increase in production of horticulture crops in the country. The high annual production growth is 7.4 percent, which is the annual industrial production growth rate in Rwanda between 1998 and 2018.

Table 3
Growth rates in production

Annual production growth	Rate (%)	Assumption and source
Low annual production growth	2.5	Conservative assumption based on the increase of horticulture production between 2017–2018
High annual production growth	7.4	Average industrial production growth rate 1998–2018 (Mwizerwa and Kayitare, 2018)

SOURCE: Elaboration by the authors.

By combining the three market penetration rates and the two growth production rates, we can develop six combined scenarios. Scenario 1 combines a low market penetration rate with a low growth in production. Scenario 6 combines a high market penetration rate and high growth in production. Scenarios 2–5 are all intermediate cases. The full set of scenarios is listed in Table 3.

Sensitivity analysis

The market potential is also susceptible to changes in the prices of equipment. Given this, a sensitivity analysis of changes ranging from -75 percent to +75 percent changes are included in the analysis to illustrate to what degree, and how the market potential changes as a result of the variation in prices.

Table 4
Scenarios for the sensitivity analysis

Parameters	Low market penetration (LMP)	Medium market penetration (MMP)	High market penetration (HMP)
Low growth of production (LGP)	**Scenario 1** LMP and LGP	**Scenario 3** MMP and LGP	**Scenario 5** HMP and LGP
High growth of production (HGP)	**Scenario 2** LMP and HGP	**Scenario 4** MMP and HGP	**Scenario 6** HMP and HGP

SOURCE: Elaboration by the authors.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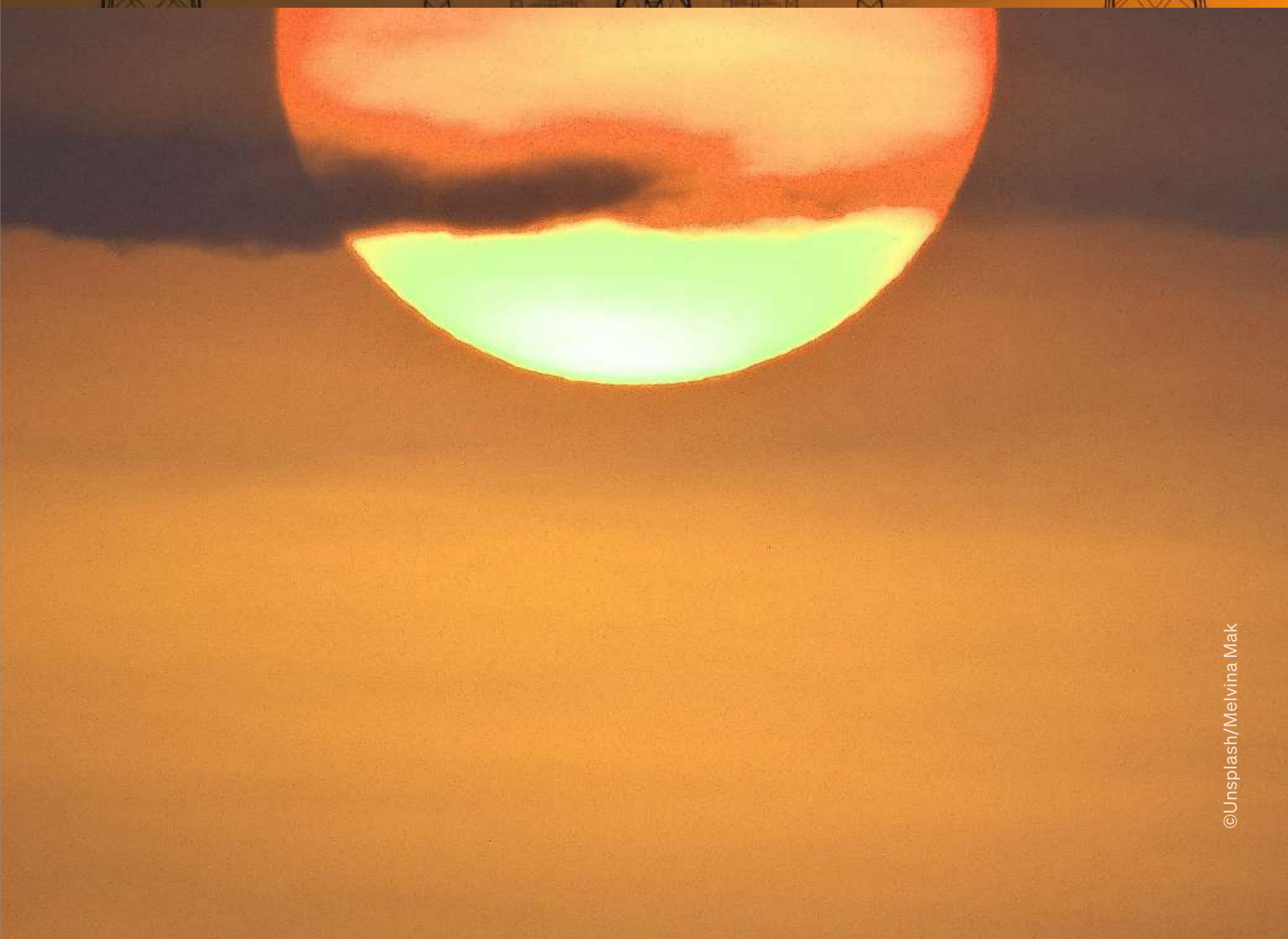
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Chapter 3
Solar energy in the milk value chain

3.1. CURRENT MILK PRODUCTION IN RWANDA

Rwanda has approximately 850 000 cattle farmers out of which 400 000 are dairy farmers (IFAD, 2016). Milk production reached 246 143 tonnes in 2016/17 (FAOSTAT, 2019) and is mostly produced by small scale farmers. The value chain remains largely informal, with only 55 percent reaching some form of sale. Of the 55 percent that is sold, around 20–25 percent is sold to cooperatives, 10–15 percent is sold directly to neighbours and 65–70 percent is sold informally IFAD, 2016 (see Figure 4). The informal sale takes place either through milk collectors or through milk hawkers. Most traders report to have a handling capacity of around 100 litres per day on average. While the exact number of milk traders is not known, rough estimates by the Milk Collectors and Traders Cluster of the Rwanda National Dairy Platform (RNDP) place the figure at around 5000–8000 traders.

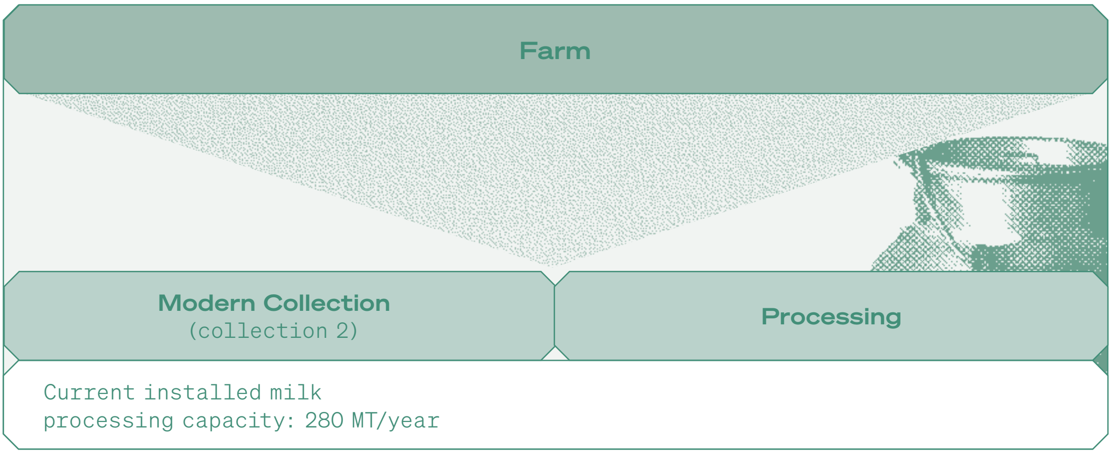

Figure 4
Current milk production chain in Rwanda

SOURCE: Diagram developed by the authors.

The milk value chain suffers from a limited number of collection points and limited processing. A review of the sector has concluded that a level of collection would need to be added to further develop the milk supply chain. At the collection level, cooling systems would be required to appropriately preserve the milk and to ensure that the milk be stored and kept safely. At the processing level, energy access represents a hurdle for the stable and smooth running of the facilities and a further value addition to milk. The current structure of the milk value chain is presented in Figure 4. Milk is produced on farms and collected or transported, but largely on an informal basis. The processing of milk into other high value-added products is a way to both provide diversified milk products and to increase economic activity within the country, but the processing capacity is currently limited. A total of 280 MT of milk is reported to be processed per year currently (Shapiro *et al.*, 2017). The country has five main milk processing plants and about 25–30 small- and medium-scale processors of cheese and other dairy products. The largest milk processor is Inyange Industries with a processing capacity of 80 MT/day and it is currently the market leader, controlling over 75 percent of the market share of processed milk and milk products in the country.

3.2 TARGET MILK PRODUCTION IN RWANDA

According to the Rwanda Livestock Master Plan, 2018, the country plans to increase the functionality of the milk supply chain by developing a structured collection of milk, thus further expanding its processing capacity with the aim to add value to milk and produce more milk-based products, see Figure 5.

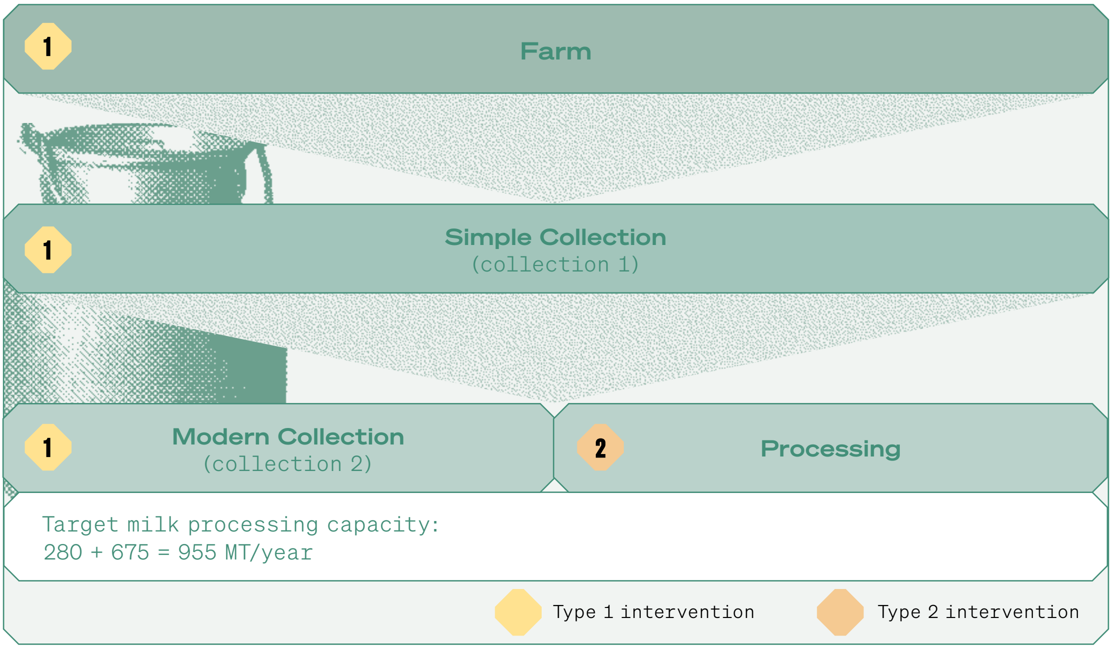

Figure 5
Target milk production value chain

SOURCE: Diagram developed by the authors.

More specifically, in terms of milk collection a new ministerial order has been set to regulate the collection, transportation and selling of milk. Under this new regulation, all milk sold in the country must first be collected at a place where quality testing is possible before being marketed. The new regulation defines two types of milk collection points:

I. **Simple milk collection points (collection 1):** this is the simplest milk collection infrastructure and consists of a structure that provides shade, is close to a road, sheltered from dust, and is equipped with clean containers.
II. **Modern Milk collection Centres (collection 2):** a modern milk collection centre is defined as one that meets several specifications related to construction and utilities (availability of water and electricity), as well as milk testing facilities.

There are currently no simple milk collection points in place. Rough estimates suggest that the country would require at least 2000 simple milk collection (IFAD, 2016) sites to handle the actual level of milk production sold by farmers.

In terms of modern collection centres, there are currently around 100 collection centres established along the lines of a modern milk collection centre (IFAD, 2016). The biggest shortfall is in the functional capacity of cooling facilities and reliable water connections. While all the MCCs have cooling facilities, part of this installed capacity is not functional largely due to disrepair or because of the electricity connection (single phase, when the coolers require 3-phase electricity). Moreover, IFAD estimates show that at least 177 MCCs are required to handle current levels of milk sold by farmers 85–100 percent of the utilization level[4].

The Rwanda Livestock Master Plan, 2018 recommends producing more value-added products in the country, specifically pasteurized milk, ultra-high temperature processing (UHT) milk and powdered milk. Furthermore, it also recommends establishing more processing capacity to process at least an additional 675 MT/day of milk into these products.

3.3 POSSIBLE SOLAR ENERGY INTERVENTIONS IN THE MILK VALUE CHAIN

Both Type 1 and Type 2 solar energy interventions are possible within the milk value chain. In terms of Type 1 interventions, solar powered cooling systems could contribute to cooling and preservation of the milk at farm level, collection 1 and collection 2 points. In terms of Type 2 solar interventions, these could provide more stable access to electricity at the processing level, see Figure 5.

Table 5
Key parameters for the analysis

Item	Value
Target processing capacity	955 MT/year
Solar interventions at farm and collection points	Solar powered cooling systems
Solar intervention at processing level	Solar PV based electricity for the processing facility

SOURCE: Own calculations based on reference data.

As outlined above, current installed processing capacity in the country is 280 MT/year. The incremental processing capacity is set to be 675 MT/year, therefore, the total target processing capacity for the milk value chain is set to be 955 MT/year.

4 These estimates are based on IFAD, 2016. The estimation of the number of MCC required are linked to the size of the MCC as well as their operation capacity. Here, it is assumed that the MCC will operative at 85-100 of their capacity.

3.3.1 Interventions at farm level

The lack of cooling facilities at the small-scale dairy farm level is a major cause of milk losses, especially when considering milk produced at night. The milk that is produced at night can only be sold the next morning, by which time it can easily spoil if not stored in a refrigerated system. Milk needs to be cooled down to 4o C as soon as the cow is milked to ensure quality. A small-scale, solar-powered milk cooler could provide a viable solution. Several types of these systems exist. Taking into consideration credit access, a small chest solar powered fridge is thought to be a feasible option due to its small size and affordable cost. Given the fact that smallholders produce less than 6 litres of milk per day, a 20-litre solar fridge was considered[5] (see Table 6 for the technical parameters). A solar milk cooler developed by SunDanzer[6] was used as a benchmark, since it is commercially available and has been one of the pioneering products in the solar milk cooler industry.

Table 6
Technical parameters for solar intervention at farm level (Type 1)

Activity	Capacity	Energy requirement	Hours used in a day	Number of days used in a year	Cost
Solar cooler	20 litres	Runs on 45 W PV module, and 24 V DC	4 hours	230	515 USD

SOURCE: Calculations by the authors based on SunDanzer reported data.

5 The smallest solar cooling system that can be found on the market is a 50 litre cooling system, please see: https://sundanzer.com/product/dcr50-dcf50-2/. A 50 litre cooling system is too big for a small holder in Rwanda that produces less than 6 litres of milk every day. Therefore, this value was used to estimate the cost of a 20 litre solar fridge using the 1/3 rule. The cost of a 20 litre was estimated to be 515 USD considering that a 50-litre capacity solar cooler costs around USD 700/system.

6 SunDanzer is one of the main companies in the field of solar energy, active also in Africa. The company was founded in 1999 by the leader of NASA's Advanced Technology Refrigeration Project with the aim of bringing real-world, sustainable solutions to off-grid refrigeration needs.

3.3.2 Interventions at milk collection centres (collection 1 and collection 2)

Milk collection centres need specific equipment to cool and test milk quality. Both the simple and modern collection centres have the potential to use solar power to operate cooling and other equipment (see Table 7 for parameters for the analysis).

Table 7
Parameters used at milk collection stage

Item	Value	Source
Number of simple collection points required	2000	(IFAD, 2016)
Number of simple collection points that exist	0	(IFAD, 2016)
Collection capacity simple MCC	100 litre/day	Assumption based on average trader collection capacity of 100 Litres (IFAD, 2016)
Number of modern collection points required	177	(IFAD, 2016)
Number of modern points that exist	100	(IFAD, 2016) (Shapiro *et al.*, 2017)
Collection capacity per modern collection point	2000 litre/day	(IFAD, 2016)

SOURCE: Data source listed in table.

While it is not specified whether the simple milk collection sheds are required to have cooling equipment, we have assumed that cooling is provided given the considerable value addition to the milk produced. Milk aggregation at a simple collection site is expected to take minimal time as milk must be delivered to a preservation facility within two hours after milking. Nevertheless, even if the milk is stored in these sheds temporarily, cooling the milk is essential to ensure the quality. A 165-litre standard solar-powered refrigerator is presumed to be used in the simple milk collection centres (see Table 8). The average milk handling capacity of milk traders (collecting milk from farmers) is around 100 litres. The 165-litre refrigerator developed by SunDanzer was used in the analysis as it is the closest size to what is commercially available. It is also of note that the SunDanzer has been one of the pioneering products in the solar milk cooler industry.

Table 8
Technical parameters for the solar cooling system at the simple milk collection centre (collection 1)

Activity	Capacity	Energy requirement	Hours used in a day	Number of days used in a year	Cost
Solar cooler	165 litres	Includes 100 W PV panel	4	230	1699 USD

SOURCE: Official SunDanzer website.

The modern milk collection centres are required to have modern facilities such as cooling, agitation and cleaning. All these facilities require energy to operate; a viable option could be to produce and supply electricity through PV panels. Therefore, the potential use of solar PV panels to provide electricity in the modern milk processing centres is analysed and based on the parameters defined in Table 9.

Table 9
Technical parameters at modern milk collection centre (collection 2)

Activity	Capacity	Energy requirement	Hours used in a day	Number of days used in a year	Cost (USD)
Pumping for milk reception	3 m3/hr	0.75 kW	2 hrs/day	230	300
Milk cooling	2500 l	4.5 kW	24	230	5000
Solar water heater for cleaning	100 l		8	230	400
Solar PV system	10 kw				3200
Total cost for the solar based intervention at collection 2 level					**8900**

SOURCE: Data collected in the field.

3.3.3 At processing level

The processing of milk into other high value-added products is a way to both provide diversified milk products and to increase economic activity within the country. Rwanda currently has a limited capacity to process milk into other products. According to the Livestock Master Plan of Rwanda, the country expects to produce more pasteurized milk, UHT and powdered milk, therefore these 3 products are included in the analysis.

The type of solar intervention at the processing stage would be the potential use of solar PV panels to supply electricity to the processing plants to process milk into pasteurised milk, UHT milk and powdered milk/butter. The analysis is based on the typical type of electricity required to convert one ton of raw milk received from the collection centres into the respective milk products. These energy requirements are outlined in Table 10.

Table 10
Parameters used to estimate PV demand at processing stage

Electricity requirement	Pasteurized milk	UHT milk	Skim milk powder
kWh/t of milk processed	55	90	90

SOURCE: Tuszyński, Diakowska and Hall, 1983.

3.4 RESULTS

Based on the current and target milk processing capacity of 280 MT/year and 955 MT/year respectively, and the solar equipment identified in the previous sections, three sets of results are presented in this section.

1

Full market potential

The market size of the identified technologies at 100 percent market penetration rate. This is also referred to as the total addressable market size[7].

2

Market potential for variations in penetration rates and growth rates

The actual market potential depends on various factors including the cost of solar technology as well as the rate at which the milk production grows over time. These changes are described in the six scenarios as outlined in the methodology section.

3

Sensitivity analysis to the price of solar equipment

For each scenario a sensitivity analysis is carried out to see the effect of changes in the cost of solar equipment on the total market size.

3.4.1 Full market potential results

Table 11 and Table 12 present the results for the full market potential for Type 1 and Type 2 interventions respectively.

For Type 1 interventions, the results indicate that the total addressable market size of farm level solar coolers would be the highest at around USD 24.6 million, followed by the market potential for solar coolers at the simple milk collection centres (USD 9.8 Million) and by the market potential for solar intervention at modern milk collection centres (USD 3.3 Million).

For Type 2 interventions, the results indicate that the potential to use solar PV systems to provide electricity to milk processing factories can range from USD 9 Million (if all milk is processed into pasteurised milk) to USD 12 million (for UHT milk and skimmed milk powder).

7 See the following link to know more: https://corporatefinanceinstitute.com/resources/knowledge/strategy/total-addressable-market-tam/.

Table 11

Market size for Type 1 interventions considering 100 percent market penetration and government target projections

Value Chain	Intervention level	Current milk processing capacity (t/yr)*	Target milk processing capacity (Qp) (t/yr)**	Qe (tonnes/yr)***	Fraction processed (%)	Price of equipment (USD)	Number of Units of equipment****	MPR (percent)	Market Size 1 (USD)
Milk	Farm level	64 400	219 650	4.6	100%	515	47750	100	24 591 250
Milk	Collection 1	64 400	219 650	37.95	100%	1699	5788	100	9 833 812
Milk	Collection 2	64 400	219 650	575	100%	8900	382	100	3 399 800

NOTES: *calculated as 280 MT/day times the number of operating days per year which is 230 days/year (this is the standard number of days considered for industrial operation considering weekends and maintenance time). **calculated as 955 MT/day times the number of operating days per year which is 230 days/year. ***Annual Processing capacity of the equipment. Data collected in the field or through literature review. ****calculated as Qp/Qe.

SOURCE: Authors calculations.

Table 12

Market size for Type 2 interventions considering 100 percent market penetration and government target projections

Value Chain	Intervention level	Current milk processing capacity (t/yr)	Target milk processing capacity (Qp) (t/yr)	Annual electricity demand (Ed) (kWh/tonnes)	Unit cost of electricity generated with a solar PV system (cpv) (USD/kW)*	MPR (percent)	Market Size 2 (USD)
Milk	Pasteurized milk	64 400	219 650	50	2273	100	9 043 561
Milk	UHT milk	64 400	219 650	90	1767	100	12 653 750
Milk	Skim milk powder	64 400	219 650	90	1767	100	12 653 750

NOTE: *The unit cost for PV electricity for pasteurized milk is higher because the energy requirement to produce pasteurized milk is lower than UHT and skim milk powder (50 kWh/tonnes compared 90 kWh/tonne). It can thus be assumed that a low-capacity PV system was used for pasteurized milk, which consequently has higher energy production costs. For UHT and Skim milk powder the energy requirements are larger and therefore, it can be assumed that a high-capacity PV system provided electricity, which has lower unit energy production costs. It should be noted that these are unit cost of production and not the capital cost. The capital cost of a low-capacity PV system would be less than the higher capacity system. These values fall within the range of 1000–3500 USD/kW reported (Belyakov, 2019). This method was not exhaustive, but it allowed to take into account the economies of scales in in PV electricity generation.

SOURCE: Calculations by the authors based on (Tuszyński, Diakowska and Hall, 1983) for energy requirement and (Enclude,2019) for cost of solar electricity in Rwanda.

3.4.2 Scenario Analysis Results

It is however unlikely that any of the considered solar technologies would penetrate the market 100 percent, considering that other technologies for milk cooling are currently available in the country. Furthermore, the real market penetration rate of the solar technologies would also depend on how the milk production in the country changes over the coming years, as well as the cost of equipment.

To capture these variations following the methodology approach, 6 scenarios have been developed using different combinations of milk production growth rates and the market penetration rates of the identified solar interventions. The 6 scenarios are outlined in Table 13.

Table 13
Scenario combinations and parameters

Scenario variables

	Low market penetration (LMP)	Medium market penetration (MMP)	High market penetration (HMP)
Low growth of production (LGP)	Scenario 1 LMP and LGP	Scenario 3 MMP and LGP	Scenario 5 HMP and LGP
High growth of production (HGP)	Scenario 2 LMP and HGP	Scenario 4 MMP and HGP	Scenario 6 HMP and HGP

Scenario parameters

Low market growth	72 863 MT/year	Assuming a 2.5 percent annual growth rate for the current processing capacity of 64 400 MT/ year	
High market growth	91 986 MT/year	Assuming a 7.4 percent annual growth rate for the current processing capacity of 64 400 MT/ year	
Market penetration rates	Low= 5%	Medium= 50%	High= 75%

SOURCE: Data as outlined in methodological section.

Table 14 presents the market potential for Type 1 solar interventions corresponding to the 6 scenarios presented in Table 13. The results indicate that the market potential for the farm level intervention is the highest in all the scenarios. More specifically, the market potential for a small portable solar cooler used at the farm level can range from USD 407 800 for scenario 1 (LMP and LGP) to USD 7 724 228 for scenario 6 (HMP and HGP)

Similarly, the results suggest that for the solar milk cooler at a simple milk collecting centre, the market potential ranges from a minimum of USD 163 104 for scenario 1 (LGP and LMP) to a maximum of USD 3 008 782 for scenario 6 (HMP and HGP).

For the solar cooling intervention at a modern milk collection centre, the market potential seems to be the lowest among the three Type 1 intervention and ranges from USD 56 515 for scenario 1 (LGP and LMP) to USD 1 068 000 for scenario 6 (HMP and HGP).

Table 14
Scenario results based on market penetration ranges and production growth rates for Type 1 interventions

Value chain	Intervention level	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
		USD	USD	USD	USD	USD	USD
Milk	Farm level	407 880	514 949	4 078 800	5 149 485	6 118 200	7 724 228
Milk	Collection 1	163 104	205 919	1 631 040	2 059 188	2 446 560	3 088 782
Milk	Collection 2	56 515	71 200	565 150	712 000	847 725	1 068 000

SOURCE: Calculations by the authors'.

As with the Type 1 intervention, the analysis also uses the 6 scenarios to estimate the market potential for Type 2 solar interventions for different combinations of milk production growth rates and market penetration rates for solar coolers. Table 15 presents the market potential estimates for the Type 2 intervention in the milk value chain for the 6 scenarios.

The results indicate that the potential for using solar PV systems to provide electricity to produce pasteurised milk can range from USD 169 708 under scenario 1 (LGP and LMP) to USD 4 057 239 under scenario 6 (HGP and HMP). Solar PV systems can also be used to provide electricity to produce UHT milk and skim milk. The analysis indicates that the market potential to use solar PV systems to produce UHT milk and skim milk Rwanda can range from USD 237 456 under scenario 1 (LGP and LMP) to USD 576 888 under scenario 6 (HMP and HGP). The reason why the market potential for using solar PV systems to produce UHT milk and skim milk is the same is due to the similar energy requirements to produce skim milk and UHT milk commercially. The complete set of results for scenarios 2–6, including quantities processed and the estimated number of units sold is available in Annex I.

Table 15
Scenario results based on market penetration ranges and production growth rates for Type 2 interventions

Value chain	Intervention level	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
		USD	USD	USD	USD	USD	USD
Milk	Pasteurized milk	169 708	270 483	1 697 082	2 704 826	2 545 623	4 057 239
Milk	UHT milk	237 456	378 459	2 374 557	3 784 592	3 561 835	5 676 888
Milk	Skim milk powder	237 456	378 459	2 374 557	3 784 592	3 561 835	5 676 888

SOURCE: Authors calculations.

3.4.3 Sensitivity Analysis Results

The sensitivity analysis aims to use the price of solar equipment for the Type 1 intervention and the price for solar PV systems for the Type 2 intervention as a factor to assess the sensitivity of the market potential for the various solar intervention considered. A sensitivity analysis is made for all 6 scenarios identified in Table 15, of which the results of 2 scenarios are presented in this section (Scenario 1 and Scenario 6) while the remaining 4 are presented in the annex.

3.4.4 Sensitivity Analysis Scenario 1: LMP & LGP

Figure 6 presents the market potential of the Type 1 solar interventions at the farm level, collection 1 and collection 2. Furthermore, it also presents the sensitivity analysis using the cost of equipment as a factor.

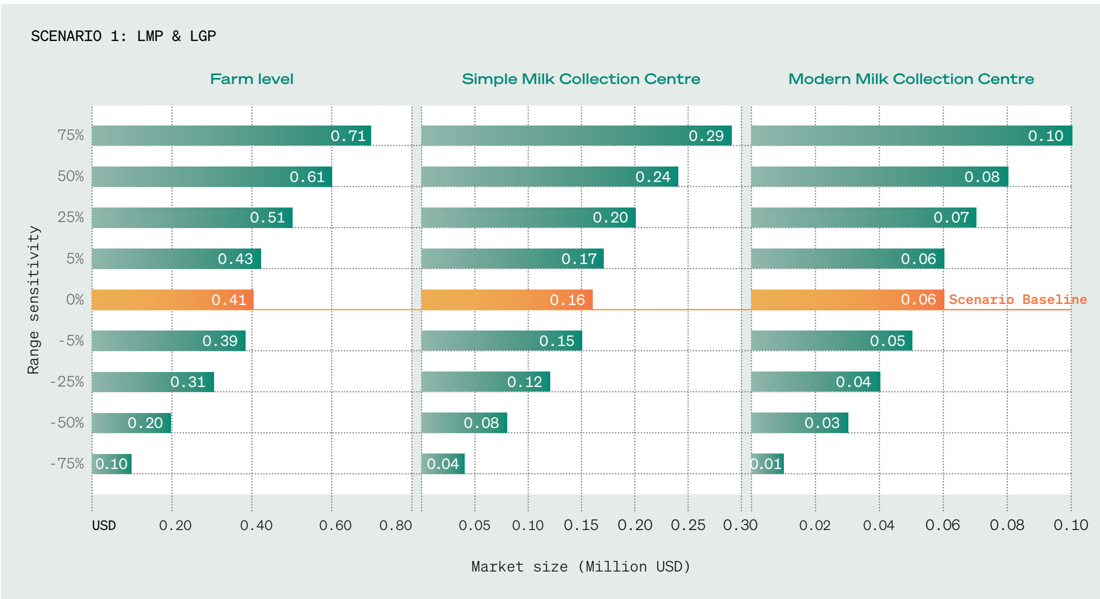

Figure 6

Market potential of Type 1 solar interventions at the farm level, simple milk collection centre and modern milk collection centre under Scenario 1

SOURCE: Authors calculations.

For the farm level solar intervention, the results suggest that at the price point of USD 515 the market potential of small-scale solar milk cooler would be around USD 0.41 million. Moreover, depending on the changes in the price of the milk cooler, the market potential can range from USD 0.10 million to USD 0.71 million. Changes in the price of equipment can vary depending on the changes in equipment efficiency, as well as government policy such as a reduction to increase import tariffs.

Similarly, at the simple milk collection centres, the market potential of a medium size solar milk cooler is estimated to be USD 0.16 million at the price of USD 1699. However, depending on the change in price of the equipment, the market size can range from USD 0.4 million (at -75 percent of the current price of equipment) to USD 0.29 Million (at + 75 percent of the current price of equipment).

For solar intervention at the modern milk collection centre, the results suggest that at the price point of USD 8900, the market potential would be around USD 0.6 Million under the LMP & LGP scenario. Also, depending on changes in the price of the equipment, the market size can range from USD 0.01 million (at -75 percent of the current price of equipment) to USD 0.10 Million (at +75 percent of the current price of equipment.

Figure 7 describes the market potential for Type 2 interventions in milk processing under scenario 1 for variations the cost of equipment.

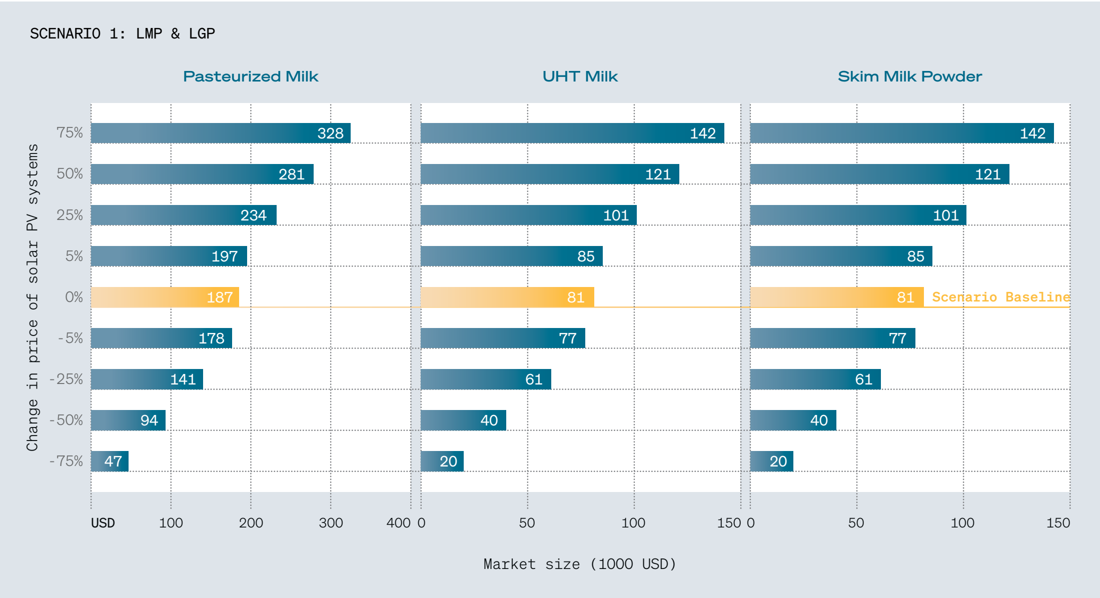

Figure 7
Market potential of Type 2 solar interventions at the processing level of the milk value chain under Scenario 1

SOURCE: Authors calculations.

At the processing stage, the analysis estimates the potential to use solar PV system to provide electricity to produce pasteurised milk, UHT milk or skim milk powder.

The results indicate that for the production of pasteurised milk, the potential to use solar PV systems is estimated to be USD 187 000 at the price of USD 2272.73 per kW. However, depending on the change in the price of the equipment, the market size can range from USD 47 000 (at -75 percent of the current price of equipment) to USD 328 000 (at +75 percent of the current price of equipment).

Similarly, to produce both UHT milk and skim milk powder production, the market potential is estimated to be USD 81 000. However, depending on the change in price of the equipment, the market size can range from USD 20 000 (at -75 percent of the current price of equipment) to USD 142 000 (at +75 percent of the current price of equipment). The similarity in market potential of UHT mil and skim milk powder is primarily due to the similarity in energy requirements to produce UHT milk and skim milk production in commercial milk processing plants.

3.4.5 Sensitivity Analysis Scenario 6: HMP & HGP

Figure 8 presents the market potential of the solar interventions at the farm level, simple milk collection centres and the modern milk collection centres at a high market penetration rate (HMP) of 75 percent[8] and high production rate (HGP) of milk in Rwanda (7.4 percent[9]). Furthermore, it also presents the sensitivity analysis using the cost of equipment as a factor.

Figure 8
Market potential of Type 1 solar interventions at the farm level, simple milk collection centre and modern milk collection centre under Scenario 6

SOURCE: Authors calculations.

For the farm level solar intervention, the results indicate that at the price point of USD 515, the market potential of a small-scale solar milk cooler would be around USD 7.72 Million. However, depending on the changes in price of the milk cooler, the market potential can range from USD 1.93 million to USD 13.52 million.

At the simple milk collection centres, the market potential of a medium size solar milk cooler is estimated to be USD 3.09 million at the price of USD 1699. However, depending on changes in the price of the equipment, the market size can range from USD 0.77 million (at -75 percent of the current price of equipment) to USD 5.41 Million (at +75 percent of the current price of equipment).

8 Based on the high potential willingness to pay of industrial consumers in a similar context (Batidzirai, B., Moyo, A., Kapembwa, M., 2018. Willingness to pay for improved electricity supply reliability in Zambia A survey of urban enterprises in Lusaka and Kitwe.)

9 Average industrial production growth rate 1998-2018 (Mwizerwa and Kayitare, 2018).

For solar intervention at modern milk collection centres, the results suggest that at the price point of USD 8900, the market potential would be around USD 1.07 Million. However, depending on the change in price of the equipment, the market size can range from USD 0.27 million (at -75 percent of the current price of equipment) to USD 1.87 Million (at +75 percent of the current price of equipment.

Figure 9 presents the market potential of Type 2 solar interventions in the milk processing stage of the value chain under scenario 1. It also presents the sensitivity analysis using the cost of equipment as a factor.

Figure 9
Market potential of Type 2 solar interventions at processing stage of the milk value chain under Scenario 6

SOURCE: Authors calculations.

At the processing stage, the analysis estimates the potential of using a solar PV system to provide electricity to produce pasteurised milk, UHT milk or skim milk powder.

Estimates suggest that to produce pasteurised milk, the potential to use solar PV systems is estimated to be USD 4 million at the equipment price of USD 2272 per kW. However, depending on the change in price of the equipment, the market size can range from USD 1 million (at -75 percent of the current price of equipment) to USD 8 million (at +75 percent of the current price of equipment).

Similarly, to produce UHT milk and skim milk powder, the market potential is estimated to be USD 2 million at the PV equipment price of USD 1766 per kW. However, depending on the change in price of the equipment, the market size can range from USD 484 000 (at -75 percent of the current price of equipment) to USD 3 million (at +75 percent of the current price of equipment). The complete set of results for sensitivity analysis under different scenarios are presented in Annex II.


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Chapter 4
Solar energy in the cereal value chain

4.1. CURRENT CEREAL PRODUCTION IN RWANDA

The cereal value chain analysed includes maize, sorghum and rice. Maize is produced throughout the country, with the east region being the largest producing region. This is also true in the case of sorghum and rice, although rice is not produced in the North. Maize and sorghum are processed into flour while paddy rice is de-husked and polished to produce rice. The cereal value chain is characterised by small holders who sell their produce to cooperatives or local traders, who in turn sell it to millers for processing.

Table 16
Average current production 2013-2018

Crop	2013–2018 Average (tonnes)
Maize	470 751
Sorghum	149 329
Rice	96 681

SOURCE: FAO, 2018.

Maize is a major crop in Rwanda and the most widely grown cereal in the country. Approximately two-thirds of the farmers dry their maize in large-scale drying facilities provided by MINAGRI through cooperatives (UNIDO, 2013). Storage is a big challenge with a current capacity of only 50 000 tonnes while the estimated need is 200 000 tonnes (Duke, 2016). Hammer mill technology is used by all millers (this technology is cheaper than roller mills) to produce maize flour, grits (for beer) and bran (for livestock feed). Sorghum is the second most grown cereal in Rwanda, however, limited information was available on the sorghum value chain. Nevertheless, sorghum has remained an important cereal in the country with a production that has remained relatively constant since 1996 with slight variations. Given that both maize and sorghum are processed into flour, the maize value chain is used as a proxy for sorghum in this analysis.

Paddy rice is the third most grown cereal in the country and is one of the priority crops in Rwanda. In 2011, the country announced the Rwanda Rice Development Strategy, which aimed to achieve self-sufficiency in rice production by 2018, and to substantially raise the competitiveness of Rwanda rice in local and regional markets. While the target was not achieved, rice production has steadily grown. Between 2010 and 2015, the production increased by one-third. The increase in production has been primarily due to the expansion of the area under cultivation as opposed to yield growth (Ghins and Pauw, 2018). Currently, around 45 percent of the paddy is milled into white rice by small and micro millers, around 22 percent of the paddy is milled in large mills in the country while 35 percent is used for seed or is lost.

4.2. TARGET CEREAL PRODUCTION

The Government of Rwanda has set specified targets for the production of rice, maize and sorghum by 2024 (Government of Rwanda, 2018). These targets are specified in Table 17. Most cereals are expected to increase yields and therefore it might be necessary to develop enough milling capacity in the country to mill the increased production of rice by 2024. These targets are used to estimate the potential market size of solar powered equipment across the cereal value chain.

Table 17
Targets for 2024 defined by the Government of Rwanda

Crop	Target Production (tonnes)
Maize	760 506
Sorghum	258 839
Rice	177 584

SOURCE: MINAGRI, 2018.

4.3 SOLAR ENERGY USE WITHIN THE CEREALS VALUE CHAIN

Milling is the main activity in the rice, maize and sorghum value chain. While traditional milling requires manual labour, all the modern milling technologies, small- or large-scale, are dependent on the availability of electricity. Given that rice is milled into white rice and both maize and sorghum are processed into flour, the rice and maize value chains were used to estimate the market potential for solar interventions. As is often the case for cereals, there is a combination of both small-scale milling as well as large-scale commercial milling operations. In terms of solar intervention this implied a different type of intervention. Consequently, two different solar interventions are considered, see Figure 10.

I. **Type 1 intervention** – Small-scale, village/community level solar mill that can mill maize, rice and sorghum. Given that rice milling significantly differs from maize and sorghum milling, two different models of solar mills are considered. One for rice milling and the other for maize and sorghum milling.

II. **Type 2 intervention** – Solar PV systems that can supply electricity to commercial cereal milling factories.

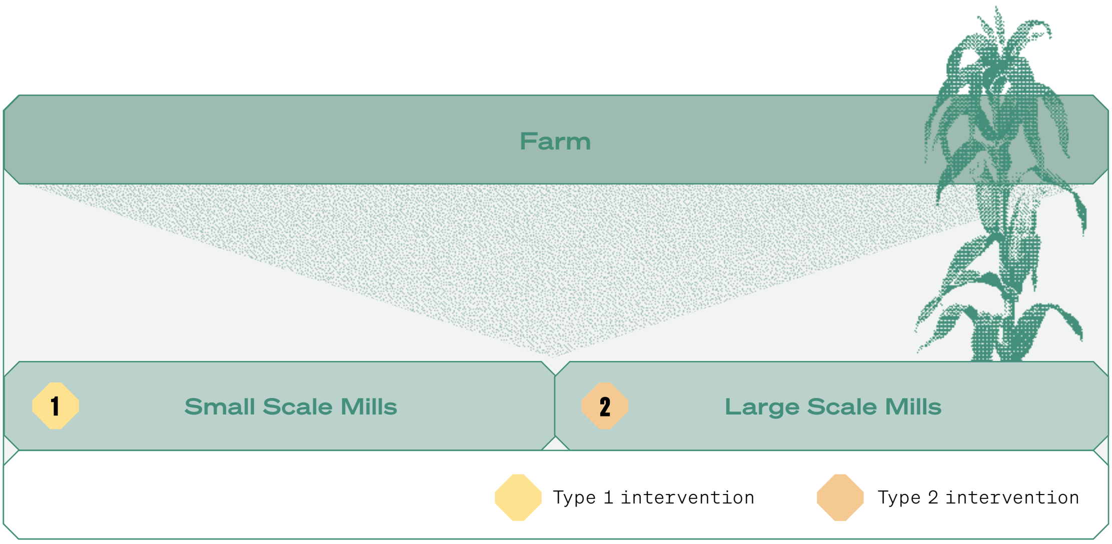

Figure 10
Solar interventions in the cereal value chain

SOURCE: Description by the authors.

Since the same mill can be used for both maize and sorghum, the production quantities of maize and sorghum are combined to estimate the market potential of solar flour mills. The main processes requiring access to electricity in the value chain are identified in Table 18.

Table 18

Main processes requiring energy during maize, rice and sorghum value chain

Cereal	Main activities during milling
Rice	The first activity is de-husking to remove the outer protective layer (husk) that encloses the rice grain. This is then followed by polishing which gives the rice its characteristic white colour.
Maize and Sorghum	Both maize and sorghum can me milled into flour. This basically involves grinding the grain into fine powder.

SOURCE: Elaboration by the authors

In terms of rice milling methods in Rwanda, currently around 45 percent of the paddy is milled into white rice by small and micro millers, often with outdated mills hence the quality of rice produced is sub-par with rice imported from other countries. Around 22–25 percent of the paddy is milled in large mills in the country while 35 percent is lost and for example, used for seed. According to this analysis it is assumed that while the rice production would increase by 2024 with respect to the government targets, the share of the processing of rice in small-scale mills and commercial mills would remain the same. Therefore, to estimate the potential for small-scale solar powered rice mills, it is assumed that in 2024 around 45 percent of the rice produced would continue to be milled by village level rice mills, and around 25 percent of the rice produced in 2024 would continue to be processed in commercial mills.

In terms of maize and sorghum milling, since both are milled into flour, the maize value chain is used as a proxy for sorghum as well. Maize distribution estimates are limited by data, but rough estimates indicate that: 35 percent of maize is consumed on farm, 24 percent is traded informally, 20 percent is lost to post-harvest handling, 9 percent is sold to Minimex, the largest cereal mill in the country, 6 percent to prisons, 2 percent to WFP, 2 percent to the National Strategic Grain Reserve, and 2 percent to other buyers (IGC, 2017). While it is unclear from this data how much maize is processed by large scale millers respectively, we assume that maize that is traded (24 percent) reaches commercial milling factories. This is in addition to the maize that is milled by Minimex (9 percent). In our analysis we consider that around 35 percent of the maize would be milled commercially.

For the small-scale mills, we assumed that the majority of the maize that is consumed where it is produced must be milled by local small-scale millers. Also, we assumed that of the 35 percent maize that is not traded, 30 percent is milled by small-scale millers while 5 percent is consumed fresh.

Finally, it is assumed that 30 percent of the maize and sorghum will be milled by small scale while another 35 will be milled in large-scale mills and the remaining amount would be used raw or is lost.

4.4. RESULTS

Based on the above assumptions, 4 scenarios are built. The first two are Type 1 interventions that estimate the potential of small scale solar powered rice and maize/sorghum milling. The other two are Type 2 interventions that estimate the potential to use solar PV to power commercial rice and maize mills.

Table 19

Main interventions analysed

Scenario	Description
Type 1 - Intervention 1	Demand for small scale solar rice huller and polisher
Type 1 - Intervention 2	Demand for small scale solar milling machine for maize and Sorghum
Type 2 - Intervention 1	Demand Potential to use PV to power large rice mills
Type 2 - Intervention 2	Demand Potential to use PV to power large maize mills

SOURCE: Elaboration by the authors.

For each intervention identified, 3 sets of results are presented.

1

Full market potential

The market size of the identified technologies at 100 percent market penetration rate. This is also referred to as the total addressable market size[10].

2

Market potential for variations in penetration rates and growth rates

The result of the six scenarios as explained in the methodology section to capture the impact of changes in production growth rates of coffee and varying levels of penetration rate solar PV systems.

3

Sensitivity analysis to the price of solar equipment

Sensitivity analyses using price of solar PV system as a factor on the results of 2 of the six scenarios, scenario 1 and scenario 6. The sensitivity analysis of the remaining 4 is scenarios is presented in the annex.

10 See the following link to know more https://corporatefinanceinstitute.com/resources/knowledge/strategy/total-addressable-market-tam/.

For Type 1 interventions, 2 commercially available solar milling systems, one for rice milling and the second for maize and sorghum milling are used as benchmark. For Type 2 interventions, the use of solar PV systems is envisaged to provide electricity to commercial rice and maize (and sorghum) mills.

For small-scale rice milling, 2 separate solar powered equipment are required: these are rice dehuskers, to remove rice husk from the grain and then a solar polisher to polish rice. The technical specifications and costs of the solar rice milling systems are based data collected from Agsol[11] solar mills by (Flammini *et al.*, 2018). Table 20 provides that data used in the estimation of the market potential under Type1 Intervention 1.

Table 20
Parameters used in the estimation of market potential for Type 1 interventions 1

Parameter	Value	Unit	Source
Current Production	96 681	Tonnes	(FAO, 2018)
Target production of	177 584	Tonnes	(MINAGRI, 2018)
% of total production processed by small scale mills (rice)	~45	Percentage	Own assumption explained above
Total Cost of Rice dehusker + polisher +batteries + PV + Cables and control systems	4850	USD	(Flammini *et al.*, 2018)
Minimum processing capacity of solar rice systems	35	Kg/hour	(Flammini *et al.*, 2018)

SOURCE: Data source listed in table.

Table 21 proved the data used to estimate the market potential of solar PV systems under the Type 2, interventions 1 scenario.

Table 21
Parameters used in the estimation of market potential for Type 2 intervention 1

Parameter	Value	Unit	Source
Energy use in a modern rice mill	53	kWh/Ton of paddy	(Goyal, Jogdand and Agrawal, 2012)
% of total production processed by commercial mills (rice)	25	percent	Own assumptions explained above
Cost of solar PV systems	1767	USD/ kW	Enclude, 2019

SOURCE: Data source listed in table.

11 https://agsol.com/innovation/.

For maize and sorghum milling, solar stone mill from a Spanish company "Seinetech "was used. The stone mill comes with a solar PV system and can produce maize or sorghum flour at the rate of 20–25 kg per hour. The data used is detailed in Table 22.

Table 22
Parameters used in the estimation of market potential for Type 1 interventions 2

Parameter	Value	Unit	Source
Current Production (maize +sorghum)	620 080	tonnes	(FAO, 2018)
Target production (maize + sorghum)	1 019 345	tonnes	(MINAGRI, 2018)
% of total production processed by small scale mills	30	%	Own assumption as explained above
Total Cost of solar cereal milling system	3650	USD	Solarmilling.com
Milling capacity	20	Kg of flour/hour	Solarmilling.com

SOURCE: Data source listed in table.

Table 23 proved the data used to estimate the market potential of solar PV systems under the Type 2, interventions 2 scenario.

Table 23
Parameters used in the estimation of market potential for Type 2 intervention 1

Parameter	Value	Unit	Source
Energy use in a modern cereals mill	23	kWh/ton of flour produced	Calculated from (Beech and Crafts-Lighty, 1980)
% of total production processed by commercial mills (rice)	35	percent	Own assumptions explained above
Cost of solar PV systems	1767	USD/kW	Enclude, 2019

SOURCE: Data source listed in table.

4.4.1 Results at 100 percent market penetration rate (total addressable market)

Table 24 and Table 25 present the first set of results that considers 100 percent penetration rates of small for Type 1 and Type 2 interventions, respectively. For Type 1 interventions, the results indicate that the total addressable market size for small scale solar power rice milling system would be around USD 20 602 800 while for the solar mill for maize and sorghum would be USD 39 938 300.

Table 24
Market size for the Type 1 interventions considering 100 percent market penetration

Value Chain	PV + equipment	Current processing capacity (t/yr)	Project processing capacity (Qp) (t/yr)	Qe (tonnes/yr)	Price of equipment (USD)	Number of Units of equipment	MPR (percent)	Market Size 1 (USD)
Rice	Solar husker polisher	43 506	79 913	18.81	4850	4248	100%	20 602 800
Cereals	Solar mill (small scale)	186 024	305 804	27.95	3650	10 942	100%	39 938 300

SOURCE: Authors calculations.

Table 25
Market size for the Type 2 interventions considering 100 percent market penetration

Value Chain	Solar PV systems to provide electricity	Current cereals processing capacity (t/yr)	Qp = total final product (tonnes/yr)	Ed=Annual electricity demand (kWh/tonnes)	Cpv=unit cost of unit of electricity generated with a solar PV system (USD/kW)	MPR (percent)	Market Size (USD)
Rice	Rice mill	24 170	44 396	52.8	1767	100%	1 499 825
Cereals	Cereals mill	217 028	356 771	23.0	1767	100%	5 252 458

SOURCE: Authors calculations.

In the case of Type 2 interventions, results suggest that the total addressable market size for using solar PV systems at commercial mills for rice would be around USD 1 499 825, while for maize and sorghum mills it would be around USD 5 252 458.

From the first set of results it is evident that the total addressable market size for Type 1 interventions is significantly larger than Type 2 interventions. This is primarily because the commercial milling capacity is still relatively limited in Rwanda and the number of small-scale solar mills that would be required in Rwanda are significantly large. It is however unlikely that small-scale milling stations would use a solar mill, or the commercial milling companies would completely rely on solar PV systems for electricity supply, as they have the option to connect to the grid as well. Moreover, the market penetration of the solar technologies would also depend on the actual changes in production quantities of cereal production in the country over the coming years, as well as the changes in cost of the solar mills and PV systems. To capture the impact of these factors, 6 scenarios were developed as described in the methodology. The results of which are presented in the next section.

4.4.2 Scenario results

Table 26 present the 6 scenarios analysed and the data used for each scenario. Details of each scenario can be found in the methodology section. Based on the 6 scenarios, the market potential for both Type 1 and Type 2 interventions are calculated corresponding to two different levels of production growth rates of rice, maize and sorghum, as well as the different penetration rates of the identified solar technologies.

Table 26
Scenario combinations and parameters

Scenario variables			
Variables	Low market penetration (LMP)	Medium market penetration (MMP)	High market penetration (HMP)
Low growth of production (LGP)	Scenario 1 LMP and LGP	Scenario 3 MMP and LGP	Scenario 5 HMP and LGP
High growth of production (HGP)	Scenario 2 LMP and HGP	Scenario 4 MMP and HGP	Scenario 6 HMP and HGP
Scenario parameters			
Target quantity at Low market growth for rice	49 224 tonnes	Assuming a 2.5 percent production growth rate for horticulture products	
Target quantity at High market growth for rice	62 143 tonnes	Assuming a 7.4 percent production growth rate for horticulture products	
Target quantity at Low market growth maize and sorghum	210 469 tonnes	Assuming a 2.5 percent production growth rate for horticulture products	
Target quantity at High market growth for maize and sorghum	265 709 tonnes	Assuming a 7.4 percent production growth rate for horticulture products	
Market penetration rates	Low= 5%	Medium= 50%	High= 75%

SOURCE: Elaboration by the authors.

Table 27 and Table 28 present the market potential of Type 1 and Type 2 interventions under the 6 scenarios respectively. The results indicate that for Type 1 interventions, the market potential for small scale solar rice milling systems can range from USD 634 623 (LMP and LGP) to USD 12 018 300 (HMP and HGP). For small scale solar milling machines for maize and sorghum on the other hand, the market potential can range from USD 1 374 408 (LMP and LGP) to USD 26 025 413 (HMP and HGP).

As shown in Table 28, for the Type 2 interventions the results indicate that the market potential for using solar PV systems to provide electricity to commercial rice mills could range from USD 52 262 (LMP and LGP) to USD 1 249 437. As for maize and sorghum mills, the results suggest that the market potential can range from USD 204 502 (LGP and LMP) to USD 4 889 062 (HGP and HMP).

Table 27
Market potential for Type 1 solar interventions under the 6 scenarios

Value Chain	Solar Interventions	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
		USD	USD	USD	USD	USD	USD
Rice	Solar husker + polisher	634 623	801 220	6 346 225	8 012 200	9 519 338	12 018 300
Cereals	Solar mill (small scale)	1 374 408	1 735 028	13 744 075	17 350 275	20 616 113	26 025 413

SOURCE: Authors calculations.

4.4.3 Sensitivity analysis

While the scenario results provide an estimate of the market potential by using different conditions of production growth rates of cereals and different market penetration rates of solar technologies identified, it does not capture the impact of changes in the cost of the solar technologies on the market size. The sensitivity analysis uses the changes in price of the solar technologies analysed as a factor to estimate the changes in the market size under that 6 scenarios presented in the previous section. The sensitivity analysis for 2 scenarios, scenario 1 and scenario 6 is presented here, while the results of the remaining 4 scenarios are presented in the annex.

Table 28
Market potential for Type 2 solar interventions under the 6 scenarios

Value Chain	Solar Interventions	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
		USD	USD	USD	USD	USD	USD
Rice	Rice mill	52 262	83 296	522 620	832 958	783 931	1 249 437
Cereals	Cereals mill	204 502	325 937	2 045 021	3 259 375	3 067 532	4 889 062

SOURCE: Authors calculations.

Sensitivity analysis scenario 1: LMP & LGP

Figure 11 presents the sensitivity analysis of the Type 1 interventions under scenario 1 (LMP and LGP). Under the LMP and LGP scenario, the results suggest that the market potential for small-scale solar rice milling systems would be USD 0.63 million at a price point of USD 4850. However, depending on the change in price of solar milling system, the market size can range from USD 0.16 million (at -75 percent of the current price) to USD 1.11 million (at +75 percent of the current price).

Figure 11
Sensitivity analysis for Type 1 interventions in cereal value chain

SOURCE: Authors calculations.

Similarly, for small-scale solar milling machine for maize and sorghum the results suggest that the market potential would be USD 1.37 million at a price point of USD 3650. However, depending on the change in price solar milling system, the market size can range from USD 0.34 million (at -75 percent of the current price) to USD 2.40 million (at + 75 percent of the current price).

For Type 2 interventions the results of the sensitivity analysis are presented in Figure 12. The results indicate that under the LMP and LGP scenario the market potential for solar PV systems to provide electricity to commercial rice mills would be USD 52 000 at a price point of USD 1767 per kW. However, depending on the changes in price of solar PV systems, the market size can range from USD 13 000 (at -75 percent of the current price) to USD 91 000 (at +75 percent of the current price).

On similar lines, for commercial maize and sorghum mills the results indicate that under the LMP and LGP scenario, the market potential for solar PV systems to provide electricity to the commercial mills would be USD 205 000 at a price point of USD 1 767 per kW. However, depending on the change in price solar PV systems, the market size can range from USD 51 000 (at -75 percent of the current price) to USD 358 000 (at +75 percent of the current price).

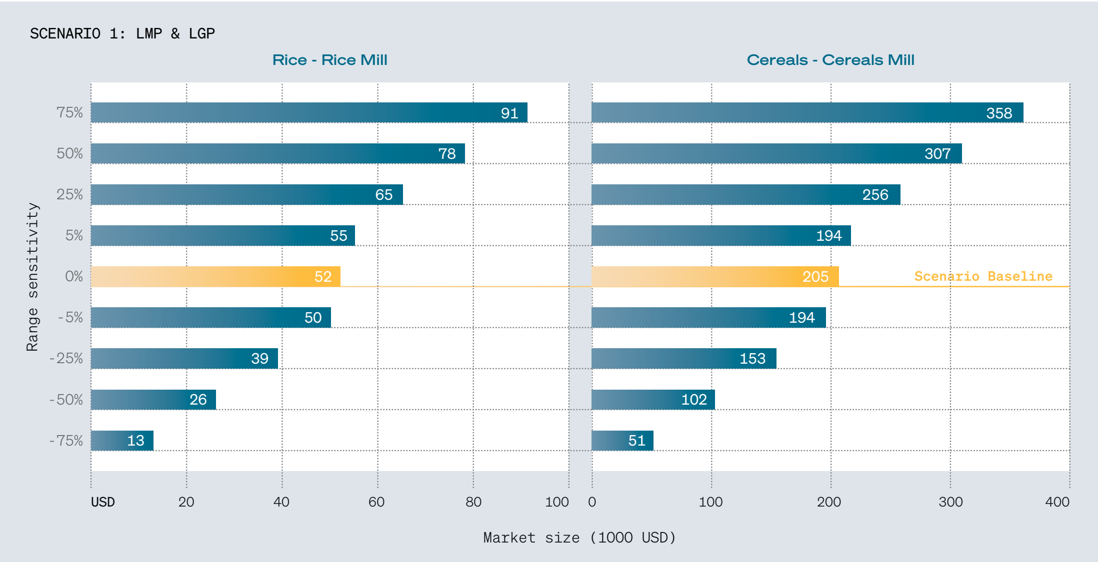

Figure 12
Sensitivity analysis for Type 2 interventions in cereal value chain

SOURCE: Authors calculations.

Sensitivity analysis scenario 6: HMP & HGP
Figure 13 presents the sensitivity analysis of the Type 1 interventions under scenario 5 (HMP and HGP). The results presented in Figure 13 suggest that the market potential for small scale solar rice milling systems would be USD 12.02 million at a price point of USD 4850. However, depending on the change in price solar milling system, the market size can range from USD 3 million (at -75 percent of the current price) to USD 21 million (at +75 percent of the current price).

Similarly, for small scale solar milling machines for maize and sorghum, the results suggest that the market potential would be USD 26.02 million at a price point of USD 3650. However, depending on the change in price solar milling system, the market size can range from USD 6.54 million (at -75 percent of the current price) to USD 45.54 million (at +75 percent of the current price).

For Type 2 interventions the results of the sensitivity analysis are presented in Figure 14. The results indicate that under the HMP and HGP scenario, the market potential for solar PV systems to provide electricity to commercial rice mills would be USD 1.2 million at a price point of USD 1767 per kW. However, depending on the changes in price of solar PV systems, the market size can range from USD 312 000 (at -75 percent of the current price) to USD 2.1 million (at +75 percent of the current price).

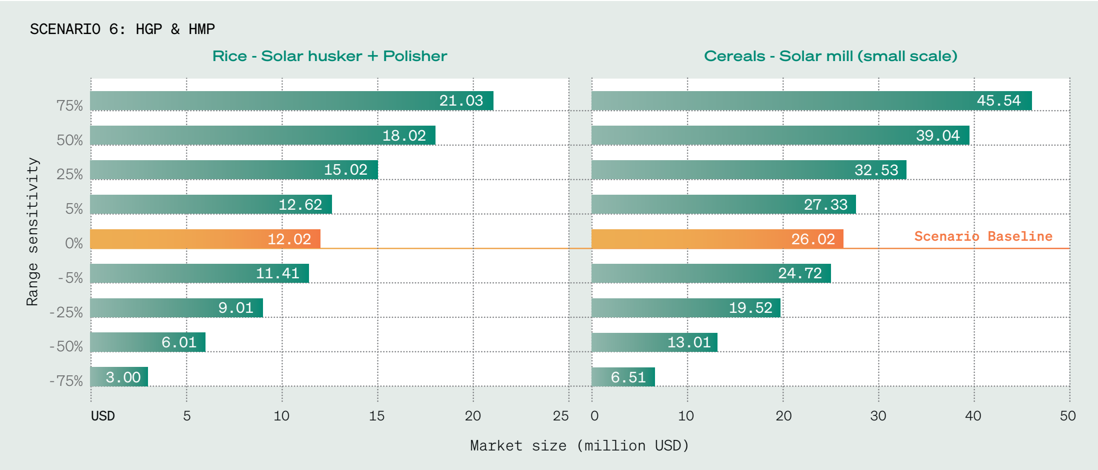

Figure 13
Sensitivity analysis for Type 1 interventions in cereal value chain

SOURCE: Authors calculations.

On similar lines, for commercial maize and sorghum mills the results indicate that under the HMP and HGP scenario, the market potential for solar PV systems to provide electricity to the commercial mills would be USD 4.8 million at a price point of USD 1767 per kW. However, depending on the change in price solar PV systems, the market size can range from USD 1.2 million (at -75 percent of the current price) to USD 8.5 million (at +75 percent of the current price).

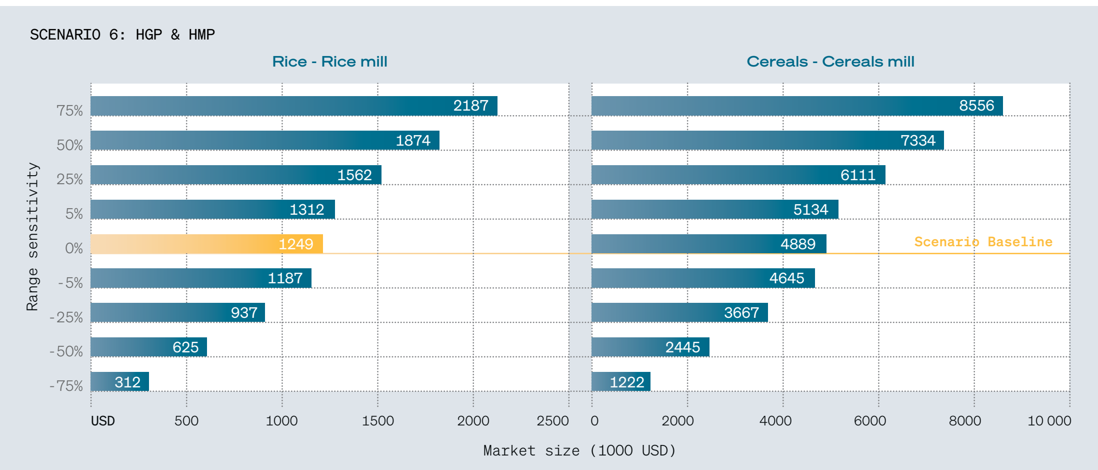

Figure 14
Sensitivity analysis for Type 2 interventions in cereal value chain

SOURCE: Authors calculations.

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Chapter 5
Solar energy in the horticulture value chain

5.1. CURRENT HORTICULTURE PRODUCTION IN RWANDA

Crops within the horticulture value chain (fruits, vegetables, roots and tubers, beans) are a key source of both domestic food supply and export revenue. In 2018, Rwanda produced a total of 5 907 362 (NISR, 2018) tonnes of horticulture products[12], equivalent to a 4 percent increase with respect to 2017. While the latest data is uncertain, in 2013 horticulture accounted for an estimated 3.2 percent of domestic GDP and 9.7 percent of agricultural GDP (Government of Rwanda, 2014). The national horticulture policy and strategic implementation plan (2014) estimates that up to one million rural households in Rwanda are estimated to grow horticultural crops, mainly for domestic use and local sales.

12 Horticulture products included here are roots, tubers, bananas, beans, fruits and vegetables.

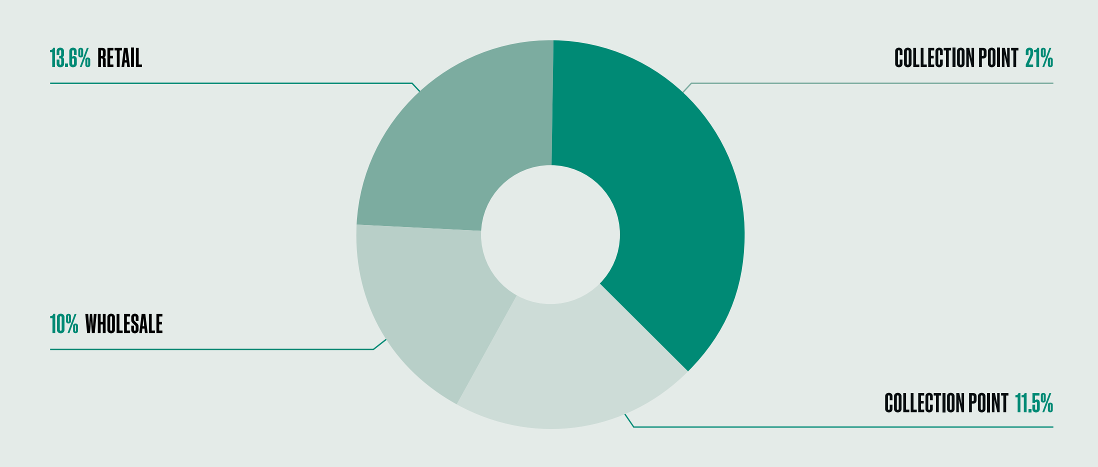

Figure 15
Tomato losses in Rwanda

SOURCE: USAID, 2018.

The horticulture value chain is rudimentary and dominated by small-scale producers and traders. Fruits and vegetables are prone to biological degradation and require cold storage to avoid rotting. Most fruits and vegetables are sold and consumed fresh. Therefore, a key challenge is the high incidence of food losses due to limited modern storage, handling and processing infrastructure. Looking at the example of tomatoes which is widely produced and consumed in Rwanda, the production reached 154 000 tonnes in 2014, up from 135 000 tonnes in 2010, although overall Rwanda remains a net importer of tomato. USAID estimated that in the tomato value chain, around 56 percent of tomatoes produced in the country are lost (USAID, 2018). A large share of these losses takes place at the collection point, wholesale and retail level. The lack of cold storage has been identified as a major factor for such high incidence of food losses. Increased access to energy for uses like cold storages and processing of horticulture crops can support the country in reducing losses as well as in increasing exports of the identified horticulture crops. At farm level, access to adequate storage after harvesting is one of the major limitations allowing for approximately only two to three days of shelf life.

Processing of horticulture products is also limited in the country and is mainly dominated by juice production, especially pineapple juice. About 1155 producer organizations/cooperatives exist in Rwanda, producing various types of horticulture crops, but only 14 of these have some sort of processing infrastructure MINAGRI and NAEB, 2014). In terms of processed food, see Table 29, fruit juice production represents the prevalent food processing activity in the producer/cooperative organisation. Preserves (pineapple, strawberry, gooseberry) and dried fruit and nuts account for the small fraction remaining (MINAGRI, 2014).

Table 29
Processed horticulture products produced in 2013

Item	Quantity sold	Share of total horticulture products processed (%)
Total processed horticulture products (tonnes)	2135	100
Juices (litre)	2 046 764	95.9*
Other products (tonnes)	87	4.1

NOTE: The remainder are strawberry, gooseberry, and dried fruits.

SOURCE: Minagri and NAEB, 2014.

5.2. TARGET HORTICULTURE PRODUCTION IN RWANDA

A typical horticulture[13] value chain in Rwanda is shown in the Figure 16

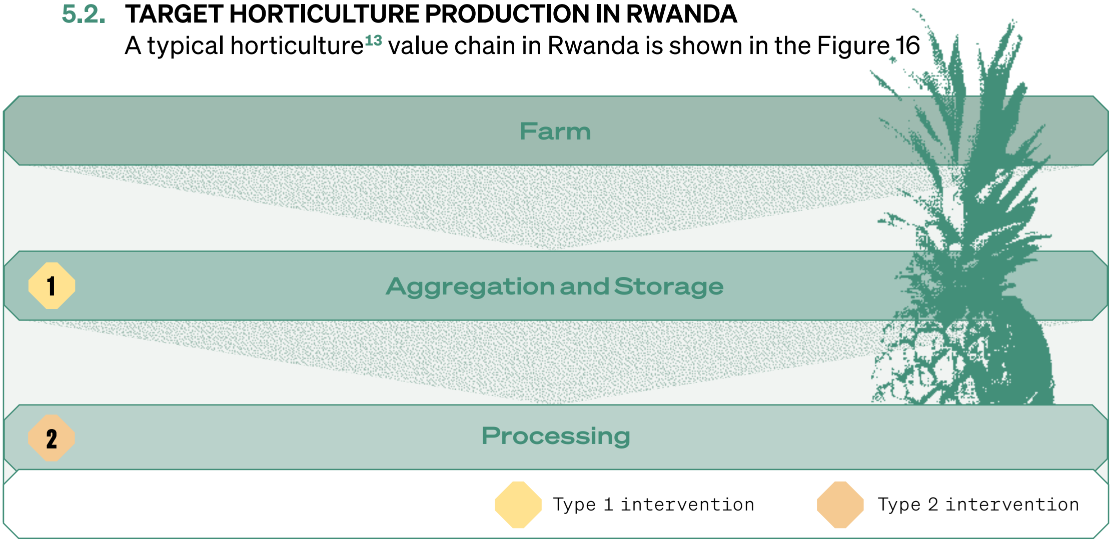

Figure 16
Typical horticulture value chain and solar energy interventions

SOURCE: Representation by the authors.

In terms of horticulture production in Rwanda, two targets for horticulture production need to be considered. Within the agriculture policy, a specific emphasis and target has been set for exporting of horticulture crops. For these horticulture crops to be exported, cold storage is required. Given the specific target set for exports, this can therefore be considered a short-term target. The national agriculture policy launched in 2018 has set the target of exporting 46 314 tonnes of horticulture crops by 2024 (MINAGRI, 2018).

On the other hand, a specific target on overall production has not been set, but production of the horticulture crops considered is expected to increase in the coming years. Considering the total of 5 907 362 tonnes of horticulture products were produced in 2017, and considering a conservative growth rate of 2.5 percent per annum, by 2024 the country is expected to produce around 7 021 996 tonnes of horticulture crops.

13 Horticulture products considered are Roots and Tubers, Beans, Banana and Fruits and Vegetables.

In terms of access to market, according to the national horticulture policy and action plan it is estimated that:

> ...over two-thirds of marketed horticultural production does not leave the district in which it is produced. Coupled with on-farm consumption, this suggests that at least three quarters of production does not leave the district in which it is grown, being consumed on-farm, consumed off-farm within the district, or lost due to deterioration beyond use.
>
> (Government of Rwanda, 2014).

This suggests that possibly only 25 percent of the produced horticulture products were marketed in a formal value chain in 2014. However, given that the country aims to develop a formal market for horticulture products, it is assumed that by 2024 the country would double the quantity of horticulture products marketed formally. Consequently, the analysis considers that by 2024 around 50 percent of the total production volume would be marketed formally requiring access to modern cold storages. This is a more ambitious and longer-term target.

As a result, two targets are considered in the analysis. The first is the government target that aims to export 46 314 tonnes of horticulture products by 2024. However, cold storage capacity developed solely for export has limited impact on locally available horticulture products which already face high level of spoilage due to lack of proper cold storage facilities. Therefore, an additional target is set that aims to develop enough cold storage capacity to handle 50 percent of the horticulture products produced in the country in 2024. As shown in Figure 16, both Type 1 and Type 2 interventions could be applicable to the horticulture value chain. Type 1 interventions can occur at the aggregation and storage stage, while Type 2 interventions would be suited for the processing stage.

In fact, while solar energy can play a role at all stages of the value chain, the major impact of using solar energy would occur by enabling the use of cold storages at the aggregation and storage stage, in addition to solar energy for processing. As explained, horticulture products are highly perishable and rot easily with increasing temperatures. Consequently, horticulture products require temperature-controlled storage infrastructure to avoid spoilage. However, lack of cold storages is a key reason for the high losses of horticulture products in many countries, including in Rwanda. Also, limited cold storage capacity prevents the horticulture products from moving further up the value chain to the processing stage where more value addition activities can take place. While traditional cold storages are powered by grid electricity, due to the country's hilly terrain, expanding the grid to the rural areas where most of the horticulture products are produced might be difficult and costly. In sum, decentralised solar powered cold storages can be a good solution to expand cold storage capacity.

In addition to the storage and aggregation stage, processing of horticulture products into value added products like fruit juice, soups, pulps etc., can be an effective way to increase employment, add value to raw horticulture products as well as to diversify food supply in the country. Processing of the horticulture products into other value-added products requires access to affordable and reliable electricity. Solar PV systems can be an alternative, sustainable and low carbon solution to power allowing to expand processing infrastructure.

5.2.1 Aggregation and Storage level interventions (Type 1)

At aggregation and storage level, solar-based cold storage equipment is considered as the most relevant intervention, namely a solar based cooling system to store the horticulture products. Given the two levels of production targets, two cold storage intervention levels are considered (see Table 30):

- **Cold storage intervention 1:** Target the export market first: as a first immediate step, the country establishes enough cold storage capacity to store 46 314 tonnes of horticulture products, equivalent to the amount that it aims to export by 2024.

- **Cold storage intervention 2:** Establish enough cold storage capacity to store 50 percent of the horticulture products produced in the country in 2024.

Table 30
Targets and production volumes used in the estimation

Item	Value
Target horticulture Production volume (2024)	7 021 996 tonnes*
Export target, 2024	46 314 tonnes exported
Cold storage 1 (Intervention 1)	Establish cold storage capacity for the 2024 horticulture export target
Cold storage 2 (Intervention 2)	Establishing cold storages at the collection points for 50 percent of the total production quantity in 2024

NOTE: Estimated based on the 2018 production levels and a growth rate of 2.5 percent per year. The growth rate used was a conservative estimate based on the production growth rate of horticulture products between 2017 and 2018, which was 4 percent.

SOURCE: Data source listed in table.

Various solar-powered cold storages are available commercially across countries at varying prices. The profiles for the cooling systems are based on data collected from relevant companies[14] (see Table 31).

Table 31
Cost and capacity of solar cold storage considered (Type 1)

Name	Capacity (tonnes)	Cost (USD)
Ecofrost (India)	5	17 000 (capex)
Cold Hubs (Nigeria)	3–5	27 000 (capex)

SOURCE: Direct communication with the companies.

5.2.2 Processing stage Intervention (Type 2)

In addition to storage, processing of horticulture crops into higher value products is a viable way to increase employment, reduce losses and increase income for farmers, but processing capacity remains limited in the country.

Given that the biggest part of processing is dedicated to fruit processing, the analysis focuses on the potential to for solar PV systems to provide electricity to fruit juice factories. Table 32 outlines the parameters used to estimate the potential market size of PV to be used in juice production factories. The target juice production volumes for 2024 was estimated based on the juice production volume in 2013 and using a growth rate of 2.5 percent per annum. The juice production quantity in 2013 was used since that was the latest data that was found and was based on data from MINAGRI and NAEB (2014).

Table 32
Energy demand assumptions made for the estimation of Type 2 Intervention

Item	Value	Unit	Source and assumption
Energy use in juice production	58	kWh/tonne	Estimated based on (Waheed *et al.*, 2008)
Increase in fruit production	2.5	%	Conservative estimate based on annual growth in horticulture production between 2017–2018
Target juice production quantity 2024	3362	Tonnes	Based on juice production capacity in 2013 and assuming annual increase of 2.5 percent

SOURCE: Data source listed in table.

14 The analysis uses two existing companies, one in India and another in Nigeria that have been successful in deploying solar powered cold storages in developing countries.

5.3. RESULTS

Considering the current production of horticulture products, the government's export targets for 2024 and the estimated production quantity of horticulture products in 2024, three main interventions were defined that are summarized in Table 33.

Table 33
Summary of the 3 solar interventions considered in the analysis

Intervention and Type	Stage of value chain	Description
Solar Cold storage Interventions 1 (Type 1)	Storage and aggregation	Target the export market first: as a first immediate step, the country establishes enough cold storage capacity to store 46 314 tonnes of horticulture products, equivalent to the amount that it aims to export by 2024
Solar cold storage interventions 2 (Type 1)	Storage and aggregation	Establish enough cold storage capacity to store 50 percent of the horticulture products produced in the country in 2024
Solar PV systems for fruit juice production (Type 2)	Processing	Potential to use solar PV systems to provide electricity to produce 3804 tonnes of fruit juices in 2024

SOURCE: Elaboration by the authors.

For each intervention identified, 3 sets of results are presented.

1

Full market potential
The market size of the identified technologies at 100 percent market penetration rate. This is also referred to as the total addressable market size[15].

2

Market potential for variations in penetration rates and growth rates
The results of the six scenarios considering variations in growth rates of horticulture production and varying levels of penetration rate of solar cold storages.

3

Sensitivity analysis to the price of solar equipment
Sensitivity analyses using price of solar PV system as a factor on the results of 2 of the six scenarios, scenario 1 and scenario 6. The sensitivity analysis of the remaining 4 is scenarios is presented in the annex.

15 See the following link to know more. https://corporatefinanceinstitute.com/resources/knowledge/strategy/total-addressable-market-tam/.

5.3.1 Results at 100 percent market penetration rate (total addressable market)

Table 34 and Table 35 present the first set of results that considers 100 penetration of the identified solar technologies for Type 1 and Type 2 interventions respectively.

For Type 1 intervention, the results indicate that the total addressable market size of for cold storage intervention 1, which relates to the government's export target for 2024, would be around USD 6 204 000. Furthermore, the total addressable market in the case of cold storage intervention 2 would be USD 470 272 000.

Table 34
Market size for the Type 1 interventions considering 100 percent market penetration

Value Chain	Solar intervention	Current processing capacity (t/yr)	Target processing capacity (Qp) (t/yr)	Qe (tonnes/yr)	Fraction processed (%)	Price of equipment (USD)	Number of Units of equipment	MPR (percent)	Market Size 1 (USD)
Horticulture	Cold storage 1	42 445	46 314	164.25	100%	22 000	282	100%	6 204 000
Horticulture	Cold storage 2	2 953 681	3 510 998	164.25	100%	22 000	21 376	100%	470 272 000

SOURCE: Authors calculations.

For the Type 2 intervention, the results indicate that the total addressable market for solar PV systems to provide electricity to juice production factories would be around USD 140 163.

Table 35
Market size for the Type 2 interventions considering 100 percent market penetration

Value Chain	Solar intervention	Current horticulture processing capacity (t/yr)	Qp (tonnes/yr)	Ed (kWh/tonnes)	Cpv (USD/kW)	MPR (percent)	Market Size 2 (USD)
Horticulture	Processing for fruit juice	2563	3362	57.6	1767	100	123 884

SOURCE: Authors calculations.

The first set of results show that the total addressable market for solar cold storages is significantly large in Rwanda. It is however unlikely that the solar cold storages would observe a 100 percent market penetration rate as the country has the option of installing grid connected cold storages as well. Moreover, the market penetration of the solar technologies would also depend on the actual changes in production quantities of horticulture products in the country over the coming years as well as the changes in cost of cold storages.

5.3.2 Scenario results

To capture the impact of changes in the future production growth rate of horticulture products and the changes is actual market penetration, 6 scenarios were defined, each including a specific set of parameters that are defined in Table 36.

Table 36
Scenario combinations and parameters

Scenario variables			
Variables	Low market penetration (LMP)	Medium market penetration (MMP)	High market penetration (HMP)
Low growth of production (LGP)	Scenario 1 LMP and LGP	Scenario 3 MMP and LGP	Scenario 5 HMP and LGP
High growth of production (HGP)	Scenario 2 LMP and HGP	Scenario 4 MMP and HGP	Scenario 6 HMP and HGP
Scenario parameters			
Target quantity at Low market growth for cold storage intervention 1	48 026 tonnes/year	Assuming a 2.5 percent production growth rate for horticulture products	
Target quantity at High market growth cold storage intervention 1	60 627 tonnes/year	Assuming a 7.4 percent production growth rate for horticulture products	
Target quantity at Low market growth for cold storage intervention 2	3 341 819 tonnes/year	Assuming a 2.5 percent production growth rate for horticulture products	
Target quantity at High market growth cold storage intervention 2	4 218 919 tonnes/year	Assuming a 7.4 percent production growth rate for horticulture products	
Market penetration rates	Low= 5%	Medium= 50%	High= 75%

SOURCE: Data as outlined in methodological section.

Table 37 presents the market potential of Type 1 interventions for the 6 scenarios. The results indicate that for cold storage intervention 1, the market potential can range from USD 322 300 for scenario 1 (LMP and LGP) to USD 6 105 000 for scenario 6 (HMP and HGP).

For cold storage intervention 2, the market potential in all scenarios is significantly higher than in cold storage intervention 1. This is primarily because the target quantity of horticulture crops to be stored in cold storage is significantly higher than that in cold storage intervention 1. The results suggest that the market potential for in cold storage intervention 2 can range from USD 22 380 000 for scenario 1 (LMP and LGP) to USD 423 819 000 for scenario 6 (HMP and HGP).

Table 37
Market potential for Type 1 solar interventions according to the 6 scenarios

Intervention	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
	USD	USD	USD	USD	USD	USD
Cold Storage Intervention 1	322 300	407 000	3 223 000	4 070 000	4 834 500	6 105 000
Cold Storage Intervention 2	22 380 600	28 254 600	223 806 000	282 546 000	335 709 000	423 819 000

SOURCE: Authors calculations

Table 38 presents the results for the 6 scenarios for Type 2 intervention at the processing stage of fruit juice. The results suggest that the market potential to use solar PV systems at would range from USD 6 043 for scenario 1 (LMP and LGP) to USD 144 473 for scenario 6 (HMP and HGP). The complete set of results for scenarios 2–6, including quantities processed and the estimated number of units sold is available in Annex I.

Table 38
Market potential for Type 1 solar interventions according to the 6 scenarios

Intervention	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
	USD	USD	USD	USD	USD	USD
Processing of fruit juice	6043	9632	60 431	96 316	90 647	144 473

SOURCE: Authors calculations.

5.3.3 Sensitivity analysis

Sensitivity analysis scenario 1: LMP & LGP

Figure 17 presents the sensitivity analysis of the Type 1 solar interventions at the storage and aggregation stage of the horticulture value chain in Rwanda at under scenario 1 (LMP and LGP).

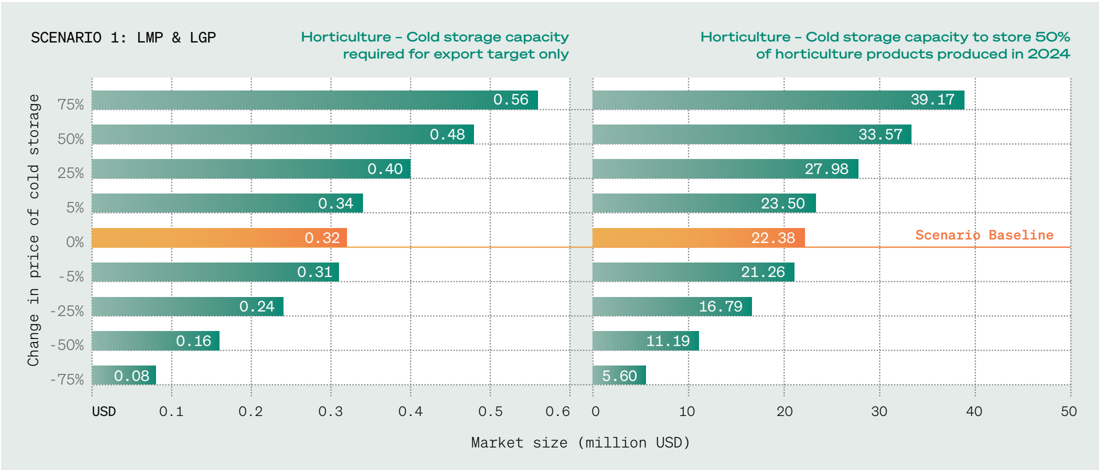

Figure 17

Sensitivity analysis using price of solar cold storage as a factor to asses impact on the market potential of Type 1 solar interventions at storage and aggregation stage under scenario 1

SOURCE: Authors calculations.

For solar cold storage intervention 1 that relates to the government's export target only, the results suggest that the market potential for the solar cold storage would be around USD 0.32 million at a price point of USD 22 000[16]. However, depending on the change in price of the solar cold storage equipment, the market size can range from USD 0.08 million (at -75 percent of the current price) to USD 0.56 million (at +75 percent of the current price).

For solar cold storage intervention 2, the results suggest that at a price point of USD 22 000 for a solar cold storage, the market potential would be around USD 22 million. Changes in the price of solar cold storage would directly impact the market potential which could range from USD 5.60 million (at -75 percent of the current price) to USD 39.17 million (at +75 percent of the current price).

Concerning the Type 2 solar intervention in the horticulture value chain, Figure 18 presents the sensitivity analysis on market potential of solar PV systems to provide electricity to fruit juice production factories using price of solar PV system as a factor.

The results suggest that the market potential for the solar PV system to be used in fruit juice factories would be around USD 6040 at a price point of USD 1767 per kW. However, depending on the change in price of the solar PV systems the market size can range from USD 1510 (at -75 percent of the current price) to USD 10 580 (at +75 percent of the current price).

16 This is based on the price of cold storages in India and Nigeria.

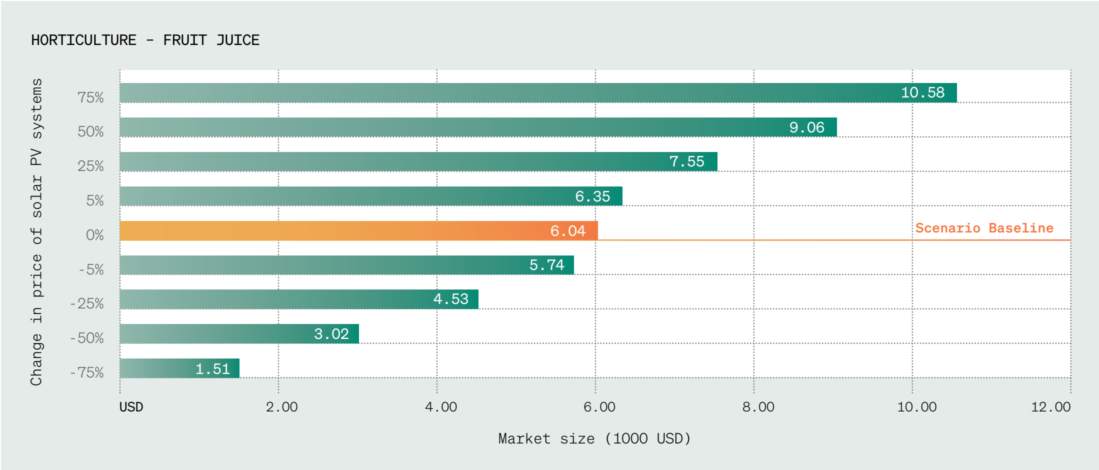

Figure 18

SOURCE: Authors calculations.

Sensitivity analysis using price of solar PV system as a factor of the market potential of Type 2 solar interventions at processing stage under scenario 1 (LMP and LGP)

Sensitivity analysis scenario 6: HMP & HGP

Figure 19 presents the sensitivity analysis of the Type 1 solar interventions at the storage and aggregation stage of the horticulture value chain in Rwanda at under scenario 6 (HMP and HGP).

Figure 19. Sensitivity analysis using price of solar cold storages as a factor of the market potential of Type 1 solar interventions at processing stage under scenario 6 (HMP and HGP).

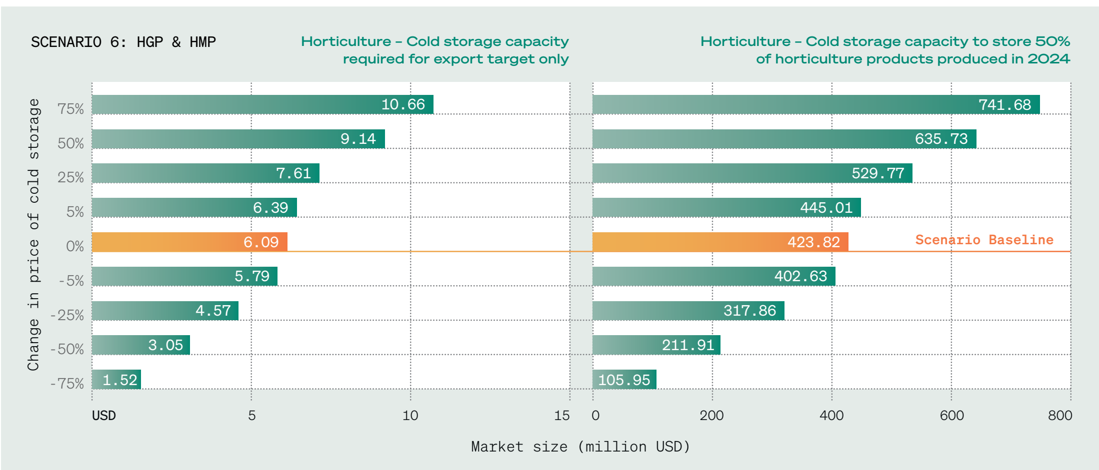

Figure 19

SOURCE: Authors calculations.

Sensitivity analysis using price of solar cold storages as a factor of the market potential of Type 1 solar interventions at processing stage under scenario 6 (HMP and HGP)

For solar cold storage intervention 1, the results suggest that the market potential for the solar cold storage would be around USD 6.09 million at a price point of USD 22 000[17]. However, depending on changes in the price of the solar cold storages equipment, the market size can range from USD 1.52 million (at -75 percent of the current price) to USD 10.66 million (at +75 percent of the current price).

For solar cold storage intervention 2, the results suggest that at a price point of USD 22 000 for a solar cold storage, the market potential would be around USD 423 million. Changes in the price of solar cold storage would directly impact the market potential which could range from USD 105 million (at -75 percent of the current price) to USD 741 million (at +75 percent of the current price).

Concerning the Type 2 solar intervention in the horticulture value chain, Figure 20 presents the sensitivity analysis on market potential of solar PV systems to provide electricity to fruit juice production factories using price of solar PV system as a factor.

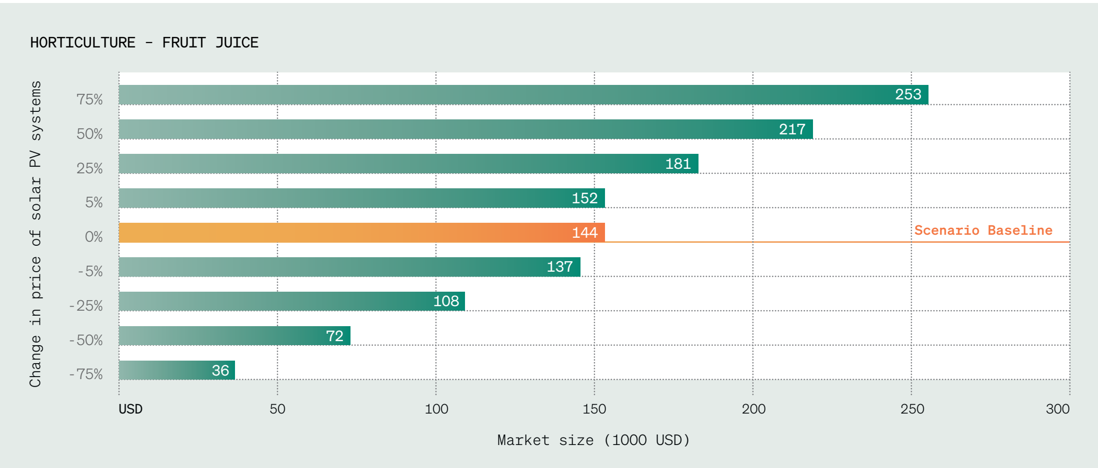

Figure 20

Sensitivity analysis using price of solar cold storages as a factor of the market potential of Type 1 solar interventions at processing stage under scenario 6 (HMP and HGP)

SOURCE: Authors calculations.

The results suggest that the market potential for the solar PV system to be used in fruit juice factories would be around USD 144 000 at a price point of USD 1767 per kW. However, depending on the change in price of the solar PV systems the market size can range from USD 36 000 (at -75 percent of the current price) to USD 253 000 (at +75 percent of the current price).

The complete set of results for sensitivity analysis under different scenarios are presented in Annex II.

17 This is based on the price of cold storages in India and Nigeria.

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Chapter 6
Solar energy in the coffee value chain

6.1 CURRENT COFFEE PRODUCTION IN RWANDA

Coffee is one of the main agriculture export products in Rwanda. Nearly all coffee production is for export and in 2016 it represented approximately 7 percent of total exports (CBI, 2018). Estimates from FAOSTAT show that the average production volume between 2013 and 2017 was 18 837 tonnes.

Table 39
Current coffee production parameters

Parameter	2013–2018 Average (tonnes)
Green coffee production (tonnes)	18 837

SOURCE: FAO, 2018.

Coffee goes through several stages before being sold in the markets. This includes harvesting of coffee bean, removal of pulp and washing followed by drying and finally roasting. In Rwanda, however, the final process of roasting of coffee does not take place and the green coffee obtained after milling is directly exported. Figure 21 illustrates the various stages of the coffee value chain in Rwanda. Coffee is first harvested as coffee cherries. The cherry is covered by a first layer of skin and pulp. During the first stage, the cherry is washed with water to remove the skin and pulp, which produces the parchment coffee, that is, the coffee bean covered by a thin layer of skin. This parchment coffee is then dried and milled to remove the second thin layer of skin to produce the green bean. This process of removing the skin and the pulp to obtain green coffee is called a wet process and the coffee produced is called fully washed coffee. Once the green coffee bean is produced, this can undergo further processing through roasting.

Figure 21
Processing along the value chain

SOURCE: Authors elaboration based on TECHNOSERVE (2018)

As the harvested coffee proceeds through the various stages of washing and processing to produce the green coffee bean, the volume of coffee reduces. The conversion rates are reproduced in Table 40.

Table 40
Coffee conversion factors along the value chain

Coffee Cherry	Parchment coffee	Green Coffee
1 kg of cherry	0.2 kg of parchment	0.16 kg

SOURCE: TECHNOSERVE, 2018

In 2016, approximately 60 percent of the coffee produced in Rwanda was reported to be fully washed, up from 35 percent in 2011/12. This was largely due to the increase in number of coffee washing stations. In 2018, there were 282 coffee washing stations operational in the country, up from only 2 in 2002. The rapid increase in the number of coffee washing stations has been attributed to active government intervention that encourage private sector to set up of coffee washing stations (CBI, 2018). Of the 282 active CWS in the country, 186 (66 percent) are privately owned.

The remaining share of coffee is processed directly by the farmers. The coffee is processed by the farmers themselves who use traditional manual methods to process the coffee. Coffee processed in this way is called semi washed coffee and is of inconsistent quality and therefore sells for lower prices in the export market. In addition, roasting of coffee in Rwanda is minimal and most of the coffee is roasted outside of the country after export. The total flow of coffee is presented in Figure 22.

Once the harvested cherries reach the coffee washing station, they are pulped, fermented and graded using flotation channels. The wet parchment is dried for 24 hours before being transported to milling stations to be processed into green coffee beans.

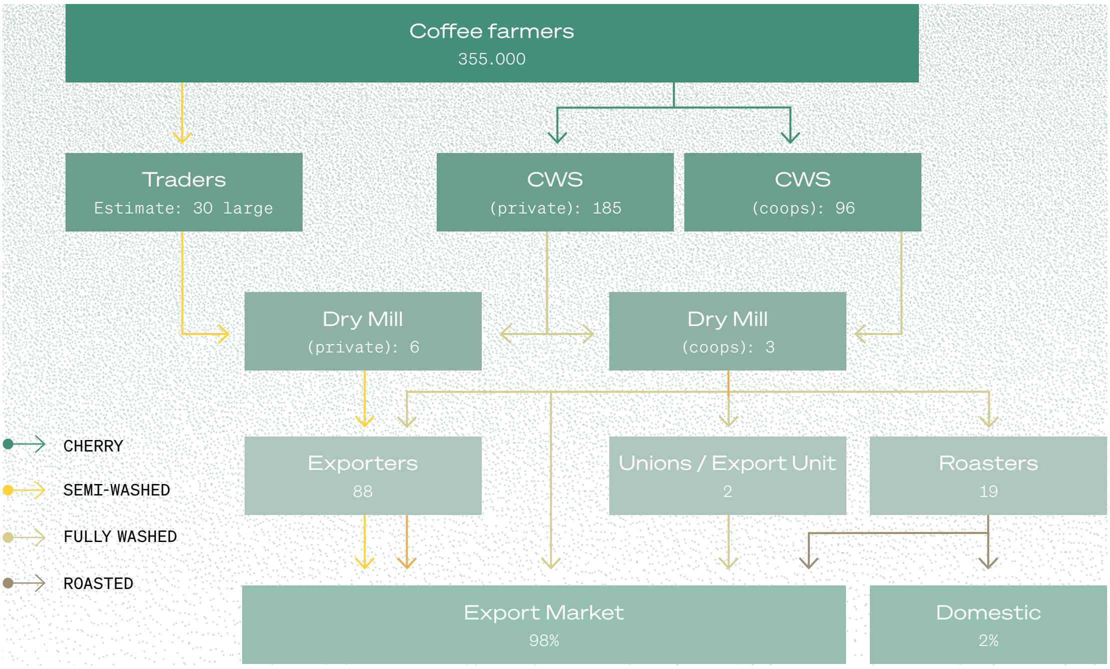

Figure 22
The coffee value chain in Rwanda

SOURCE: Centre for the Promotion of Imports from developing countries (CBI), 2018.

The roasting of coffee is limited in Rwanda, and is mostly done once the coffee is exported. As explained above, the main processing of coffee in Rwanda takes place at the coffee washing stations and in the milling stations. While there has been a significant increase in the number of washing stations in the country, currently only 29 percent of the coffee washing stations in the country are reported to be connected to the grid (CBI, 2018). It is not clear how the remaining coffee washing station satisfy their energy demand, but it is likely that the washing process is done manually, and diesel generators might be used for other purposes such as lighting etc. Given the relatively low demand for electricity at the coffee washing stations as well as the fact that coffee washing station are distributed across the country, decentralised solar PV systems can be used to power the CWS that are currently not connected to the grid.

Moreover, based on the data from CBI (2018), it is estimated that country has enough washing stations installed to process 83 percent of the coffee produced in Rwanda. This coupled with the fact that around 71 percent of the CWS do not have access to electricity means that around 59 percent of the coffee produced is processed at CWS that are currently not connected to the grid (see Table 41).

Table 41
Volume of coffee processed in off grid washing stations

Parameter	Value
Share of CWS not connected to the grid (%)	71
Share of coffee that passes through coffee washing stations (%)	83
Share of coffee processed in CWS and not connected to the grid (%)	59

SOURCE: CBI (2018) and own calculations.

Regarding dry milling of coffee beans, access to electricity is critical to run the milling machinery to produce green coffee. Similar to coffee washing stations, solar PV systems can be used to supply renewable, clean and decentralized electricity to the milling stations as well.

Based on the above, the main stages within the current coffee value chain where solar energy interventions can be made are at the coffee washing stations and at the milling stations.

In addition to coffee washing stations and milling stations, coffee roasting is a major value addition activity in the coffee value chain and if pursued, can bring increased revenues from the export of roasted coffee. While currently coffee roasting capacity is still quite limited in Rwanda in the medium term, this capacity should be expanded to further modernize the coffee value chain in Rwanda. Roasting of coffee also requires reliable access to electricity and solar PV systems can be deployed that the coffee roasting stations to satisfy the electricity demand. In terms of future targets, the Government of Rwanda aims to increase the coffee yield per tree from 3kg to 4 kg by 2024 (see Table 42). Together with data on current coffee production from FAOSTAT this information is used to estimate the projected coffee production in the year 2024.

Table 42
Target growth for the coffee sector

Parameter	Value
Coffee yield (kg/tree) 2018	3
Coffee yield (kg/tree) 2024	4
Target Production (tonnes) 2024	92 615

SOURCE: (MINAGRI, 2018) and own calculations.

6.2 SOLAR INTERVENTIONS CONSIDERED

Given the specific set up of the coffee value chain in Rwanda, the main stages where solar energy can be employed is at the coffee washing stations and coffee milling stations. Moreover, while currently Rwanda does not have significant coffee roasting stations, the analysis also estimates the potential to use solar PV systems at coffee roasting station should the government decide to further develop the coffee value chain by establishing and expanding roasting activities within Rwanda. Figure 23 exhibits the solar interventions considered in the coffee value chain.

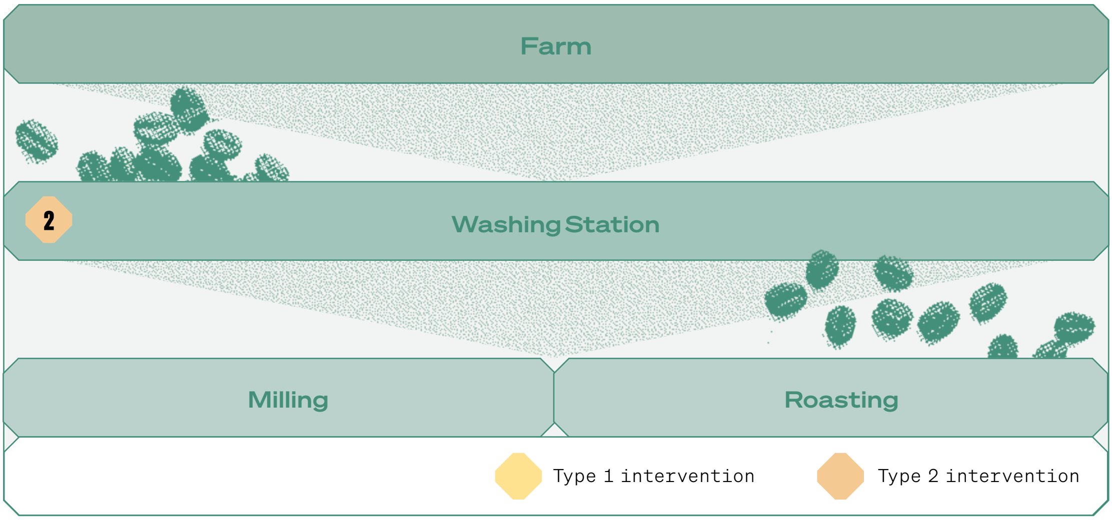

Figure 23
Typical coffee value chain and solar energy interventions

SOURCE: Representation by the authors.

To estimate the needs of solar PV systems at the coffee washing stations, coffee milling station and for coffee roasting, the energy demand for each of these activities is required. It is also essential to know the costs of PV systems currently available in Rwanda. This information was collected from peer reviewed publications as well as from the field work done by Enclue in early 2019. The values are detailed in Table 43.

Table 43
Energy demand assumptions made for the estimation of Type 2 Intervention

Solar Intervention (Type 2)	Annual electricity demand (kWh/tonnes)*	Solar system cost (USD/kW)**
Coffee washing station	39.7	2273
Coffee drying mills	31.4	1767
Coffee roasting	40.0	1767

SOURCE: *Data collected by the authors for Latin-American coffee mills, **Data provided by Enclude, 2019.

6.3 RESULTS

The total production of coffee in Rwanda is around 18 837 MT (FAO, 2018) and around 83 percent of all coffee produced was processed in the CWS. An estimated 71 percent of the coffee washing stations are not connected to the grid and process around 59 percent of all coffee produced in the country (71 percent of 83 percent.) Given that the coffee value chain has 3 major stages, 3 distinct Type 2 interventions were analysed.

- **Intervention 1** considers the option of using solar PV system to provide electricity to washing stations that are currently not connected to the grid. Once the coffee berries are washed, they are then milled to produce green coffee (parchment coffee).

- **Intervention 2** examines the potential to use solar PV to run coffee milling operations in Rwanda. Although currently limited in the country, roasting coffee is an important step in the coffee value chain and can provide job opportunities and add value before exporting the product.

- **Intervention 3** examines what potential might exist for PV solar systems to be used to expand coffee roasting in Rwanda.

Table 44
Summary of the solar interventions considered in the analysis

Scenario	Definition
Intervention 1	Potential to use solar PV at coffee washing stations that are not connected to the grid
Intervention 2	Potential to use solar PV at coffee milling facilities
Intervention 3	Potential to use solar PV for coffee roasting

SOURCE: Elaboration by the authors.

For each intervention identified, 3 sets of results are presented.

1

Full market potential

The market size of the identified technologies at 100 percent market penetration rate. This is also referred to as the total addressable market size[18].

2

Market potential for variations in penetration rates and growth rates

The result of the six scenarios as explained in the methodology section to capture the impact of changes in production growth rates of coffee and varying levels of penetration rate solar PV systems.

3

Sensitivity analysis to the price of solar equipment

Sensitivity analyses using price of solar PV system as a factor on the results of 2 of the six scenarios, scenario 1 and scenario 6. The sensitivity analysis of the remaining 4 is scenarios is presented in the annex.

6.3.1 Results at 100 percent market penetration rate (total addressable market)

Table 45 presents the first set of results that considers 100 percent penetration rates of the PV systems at the washing stations, dry milling stations as well as roasting stations. The results indicate that the total addressable market size for PV systems for electricity supply at coffee washing station would be around USD 3 025 840, while at the dry mills and roasting station it would be USD 371 880 and USD 189 705 respectively.

Table 45
Market size for the three interventions considering 100 percent market penetration

Value Chain	Solar intervention	Current coffee processing capacity (t/yr)	Qp (tonnes/yr)	Ed (kWh/tonnes)	Cpv (USD/kW)	MPR (percent)	Market Size 2 (USD)
Coffee	Washing station (CWS)	69 461	92 615	39.7	2273	100	3 025 840
Coffee	Dry mills	13 892	18 523	31.4	1767	100	371 880
Coffee	Roasters	5557	7409	40.0	1767	100	189 705

SOURCE: Authors calculations.

18 See the following link to know more. https://corporatefinanceinstitute.com/resources/knowledge/strategy/total-addressable-market-tam/.

The first set of results show that the total addressable market for solar PV systems to supply electricity is largest at the coffee washing station and least at the roasting stations. It is however unlikely that all the coffee washing stations or dry milling station, or roasting station would use PV systems to supply electricity as they have the option of connecting to the grid as well. Additionally, the market penetration of the solar technologies would also depend on the actual changes in production quantities of coffee in the country over the coming years as well as the changes in cost of PV systems. To capture the impact of the changes in costs and production volumes of coffee as well as penetration rates, 6 scenarios were developed as described in the methodology. The results of which are presented in the next section.

6.3.2 Scenario results

Table 46 presents the 6 scenarios that are analysed and the corresponding assumptions made.

Table 46
Scenario combinations and parameters

Scenario variables			
Variables	Low market penetration (LMP)	Medium market penetration (MMP)	High market penetration (HMP)
Low growth of production (LGP)	Scenario 1 LMP and LGP	Scenario 3 MMP and LGP	Scenario 5 HMP and LGP
High growth of production (HGP)	Scenario 2 LMP and HGP	Scenario 4 MMP and HGP	Scenario 6 HMP and HGP
Scenario parameters			
Target quantity at Low market growth for Coffee Washing Stations	88 917 tonnes/year	Assuming a 2.5 percent production growth rate for coffee production	
Target quantity at High market growth Coffee Washing Stations	141 716 tonnes per year	Assuming a 7.4 percent production growth rate for coffee production	
Target quantity at Low market growth for dry mills	17 783 tonnes/year	Assuming a 2.5 percent production growth rate for coffee production	
Target quantity at High market growth dry mills	28 343 tonnes/year	Assuming a 7.4 percent production growth rate for coffee production	
Target quantity at Low market growth for Coffee roasters	7113 tonnes/year	Assuming a 2.5 percent production growth rate for coffee production	
Target quantity at High market growth Coffee roasters	11 337 tonnes/year	Assuming a 7.4 percent production growth rate for coffee production	
Market penetration rates	Low= 5%	Medium= 50%	High= 75%

SOURCE: Data as outlined in methodological section.

Table 47 presents the market potential of solar PV systems for the three interventions analysed across the 6 scenarios. The results indicate that the potential form solar PV systems at coffee washing stations is the highest, and can range from USD 145 250 to (LMP and LGP) to USD 3 472 511 (HMP and HGP).

At the dry milling stations the potential is second highest and ranges from USD 17 851 (LMP and LGP) to USD 426 777 (HMP and HGP) while at the coffee roasting stations, the potential seems to be the lowest ranging from USD 9106 (HMP and HGP) to USD 217 709 (HMP and HGP).

The complete set of results for scenarios 2–6, including quantities processed and the estimated number of units sold is available in Annex I.

Table 47
Market potential for solar interventions according to the 6 scenarios (USD)

Value chain	Solar PV system for electricity supply	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Coffee	Washing station (CWS)	145 250	231 501	1 452 499	2 315 007	2 178 748	3 472 511
Coffee	Dry mills	17 851	28 452	178 514	284 518	267 772	426 777
Coffee	Roasters	9106	14 514	91 064	145 139	136 596	217 709

SOURCE: Authors calculations.

6.3.3 Sensitivity analysis

Sensitivity analysis scenario 1: LMP & LGP

Figure 24 presents the sensitivity analysis of the three interventions within the coffee value chain in Rwanda at under scenario 1 (LMP and LGP).

Under the LMP and LGP scenario, the results suggest that the market potential for solar PV systems at coffee washing stations would be USD 145 000 at a price point of USD 2273 per kW of solar electricity capacity. However, depending on the change in price solar PV systems, the market size can range from USD 36 000 (at -75 percent of the current price) to USD 254 000 (at +75 percent of the current price).

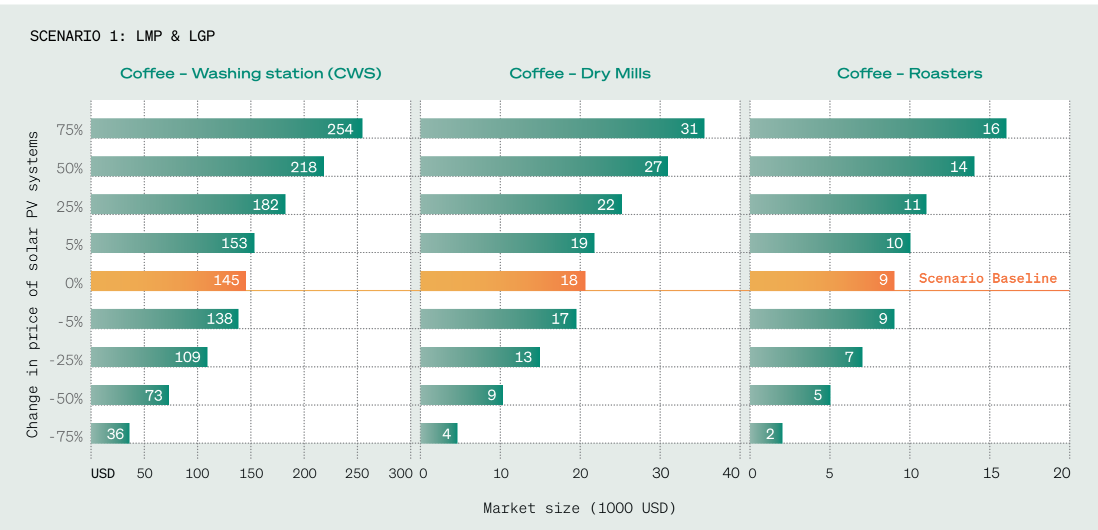

Figure 24
Sensitivity analysis using price of solar PV systems a factor to asses impact on the market potential of 3 interventions along the coffee value chain under scenario 1

SOURCE: Authors calculations.

At the coffee milling stations, the results suggest that under the LMP and LGP scenario, the market potential for solar PV systems would be USD 18 000 at the price pointe of USD 1767 per kW of solar electricity capacity. However, changes in the cost of PV systems would have an impact the market potential pf solar PV systems which would range from USD 4000 (at -75 percent of the current price) to USD 31 000 (at +75 percent of the current price)

At the coffee roasting stations, the results suggest that the market potential for solar PV systems would be USD 9000 at the price pointe of USD 1767 per kW of solar electricity capacity. However, changes in the cost of PV systems would have an impact the market potential pf solar PV systems which would range from USD 2000 (at -75 percent of the current price) to USD 16 000 (at +75 percent of the current price)

Sensitivity analysis scenario 6: HMP & HGP

Figure 25 presents the sensitivity analysis of the three interventions within the coffee value chain in Rwanda at under scenario 1 using (HMP and HGP).

Under the HMP and HGP scenario, the results suggest that the market potential for solar PV systems at coffee washing stations would be USD 3473 000 at a price point of USD 2273 per kW of solar electricity capacity. However, depending on the change in price solar PV systems, the market size can range from USD 868 000 (at -75 percent of the current price) to USD 6 077 000 (at +75 percent of the current price).

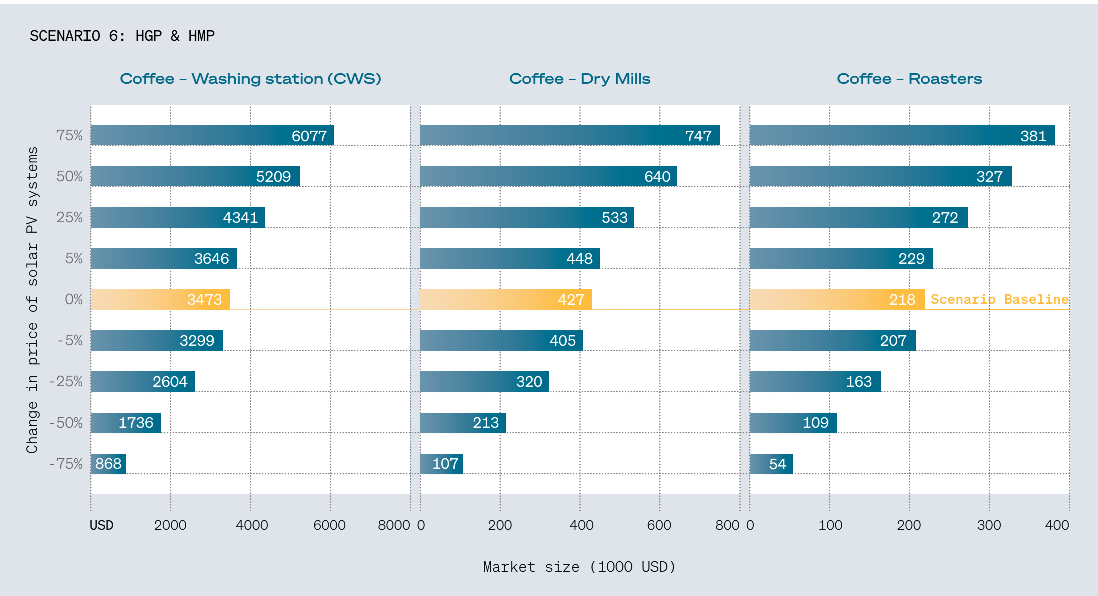

Figure 25
Sensitivity analysis using price of solar PV systems a factor to asses impact on the market potential of 3 interventions along the coffee value chain under scenario 6

SOURCE: Authors calculations.

At the coffee milling stations, the results suggest that under the HGP and HMP scenario, the market potential for solar PV systems would be USD 427 000 at the price pointe of USD 1767 per kW of solar electricity capacity. However, changes in the cost of PV systems would have an impact on the market potential pf solar PV systems which would range from USD 107 000 (at -75 percent of the current price) to USD 747 000 (at +75 percent of the current price).

At the coffee roasting stations, the results suggest that the market potential for solar PV systems would be USD 218 000 at the price pointe of USD 1767 per kW of solar electricity capacity. However, changes in the cost of PV systems would have an impact the market potential pf solar PV systems which would range from USD 54 000 (at -75 percent of the current price) to USD 381 000 (at +75 percent of the current price).

The complete set of results for sensitivity analysis under different scenarios are presented in Annex II.

Chapter 7
Solar energy in the tea value chain

7.1 CURRENT TEA PRODUCTION AND VALUE CHAIN IN RWANDA

Tea is a major export crop for Rwanda. In 2019 the country exported 31 157 tonnes of tea generating around USD 86 million for the country (FAOSTAT, 2020). Production of tea started in the 1950s and has since then been one of the strongest agriculture sub sectors in the country. Over the last decade, the production of tea has witnessed a constant rise, increasing from around 20 000 tonnes in 2009 up to over 30 000 tonnes in 2018 (see Figure 26). Almost all tea produced in the country is exported and tea exports represent 35 percent of national exports (FAO, 2016).

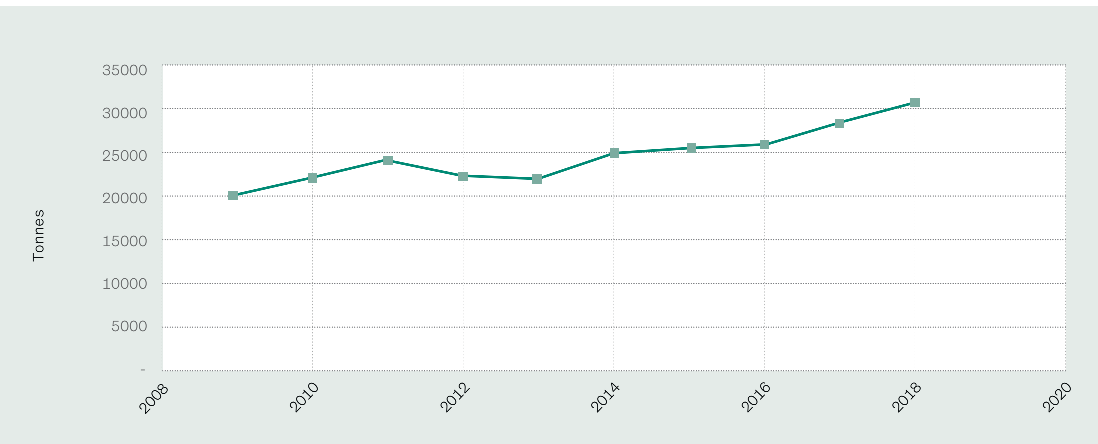

Figure 26
Tea production in Rwanda

SOURCE: FAOSTAT, 2020.

The value chain of tea in Rwanda consists of three main steps. The first step is the cultivation and harvest of fresh tea leaves. At the second step, fresh tea leaves are processed into "made tea" by the country's tea processing factories, and finally, made tea is exported out of the country. The cultivation and harvest of tea in Rwanda is done by both smallholder farmers who are organized into cooperatives, as well as large tea estates that are owned by the tea processing factories (Figure 27).

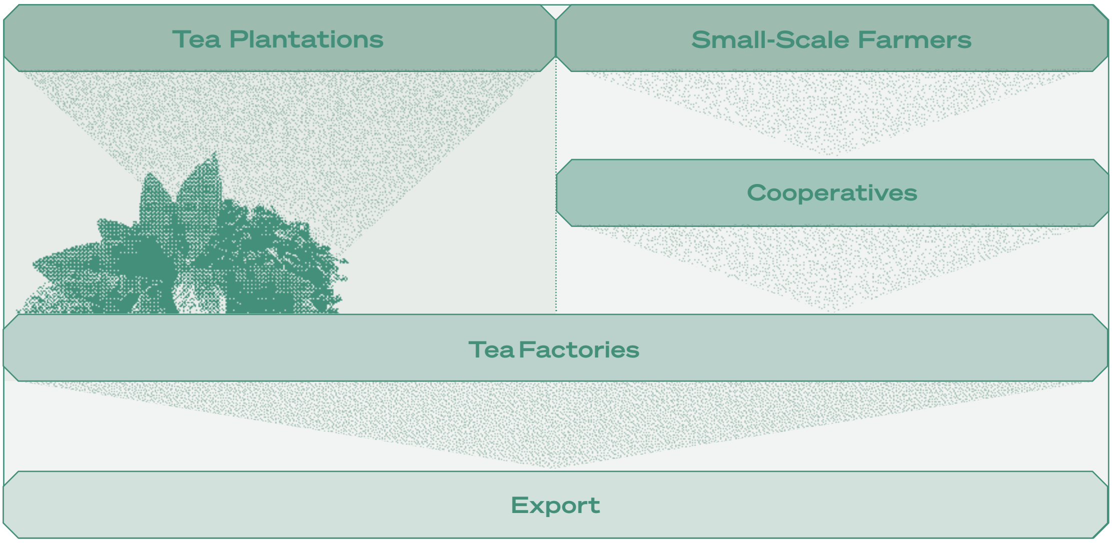

Figure 27
Tea value chain in Rwanda

SOURCE: Adapted from ILO, 2017.

Export value of tea grew from USD 30 million in 2009 to USD 50 million in 2018 (FAOSTAT, 2020). In July 2012, the Government of Rwanda passed a reform on the pricing mechanism of green tea leaf, which was enforced at the end of 2012. The reform links green leaf prices to international market prices for 'made tea'. The tea sector is the source of about 60 000 jobs as well as 42 000 smallholder tea growers.

Overall, the entire production process is managed by large tea estates, land sharing cooperatives and smallholder farmers. Smallholder farmers sell their harvested tea leaves to tea cooperatives, which in turn sell the tea leaves to tea processing factories. In addition, the tea factories also own tea plantations which provide part of the green leaf supply to the tea factories. Processed tea is directly exported by the tea factories. Once the tea is processed in the factories, most of it is then traded in Kenya where brokers participate in the auctioning of tea from Rwanda. After the auction the tea is transported to the destination country where it may be blended with other teas and packaged before being retailed.

7.2 TARGET TEA PRODUCTION IN RWANDA

Given that tea export is of strategic interest for the government of Rwanda, the country has set specific targets for the future production capacity in the country, see Table 48.

Table 48
Current tea production and target tea production in Rwanda

Crop	2016	2017	2018	2019	2020	2021	2022	2023/24
Tea (tonnes/year)	28 000	30 240	32 659	35 109	37 566	40 572	43 817	46 361

SOURCE: Strategic plan for agriculture transformation 2018-2024

Due to its importance for both the country's export income and its employment generation capacity, the Government of Rwanda envisages tea production to reach 46 361 tonnes by 2023/24 from the 37 566 tonnes in 2020. Currently there are 15 tea production factories in operation in Rwanda, and by the 2023/24, eighteen tea production factories are expected to be operational in the country. (MINAGRI, 2018)

7.3 SOLAR INTERVENTION IN TEA FACTORIES

Tea manufacturing is energy intensive and needs both electricity and thermal heat for processing. The main activities performed in a tea processing factory are withering, fermenting, and drying.

Solar energy interventions for the tea production value chain would mostly be related to solar PV systems to produce electricity (Type 2 interventions), as no standalone solar equipment (Type 1 interventions) exist commercially for the harvesting and processing of tea. Tea factories consume large amounts of electricity, therefore, Type 2 interventions entailing the installation of solar PV panels to produce electricity that can power the tea processing factory would be very relevant.

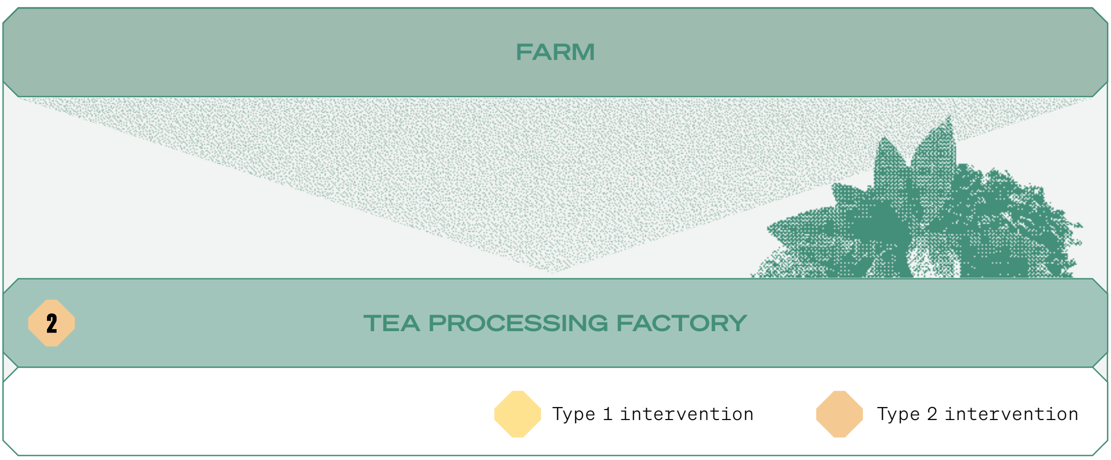

Figure 28
Typical tea value chain and solar energy interventions

SOURCE: Adapted by the authors from Foster and Graham, 2015.

Around 4.2 kg of fresh tea leaves are needed to produce 1 Kg of 'made tea'[19]. The amount of electricity consumed are reported in Table 49, including both amounts and costs for electricity from the grid and off grid (from diesel generators). The estimation for the market potential is based on the data as reported in Table 48 and 49.

Table 49
Tea production requirements and energy use and costs

Parameter	Value
Amount of diesel consumed per month to generate electricity	15 281 tonnes/year
Cost of diesel consumed per month to generate electricity	3657 tonnes/year
Amount of diesel consumed per month to generate electricity	141 362 kWh/month
Cost of diesel consumed per month to generate electricity	RWF/month 14 501 086
Amount of diesel consumed per month to generate electricity	3045 litres/month
Cost of diesel consumed per month to generate electricity	RWF/month 2 808 981

SOURCE: Data collected in the country.

7.4 RESULTS

The estimations of the market potential for solar energy in the tea value chain are based on considering the current production of tea and the government target for 2023/24 and Type 2 interventions.

19 The data presented is based on data reported through direct communication by the Sorwathe tea factory. This company is one of the largest tea producing factories in the country and should be representative of the energy consumption levels in the sector. The data was also cross-referenced with peer reviewed data on energy use in tea processing in other countries in Africa and was found consistent with them (REF: https://www.sciencedirect.com/science/article/abs/pii/S1364032115013398). Furthermore, smaller companies would potentially have less efficient processing systems which consume higher amounts of electricity and consequently the market size could possibly be considered slightly underestimated.

Three sets of results are presented:

1

Full market potential

The market size of the identified technologies at 100 percent market penetration rate. This is also referred to as the total addressable market size and represents the full market size of the type 2 interventions in the tea value chain.

2

Market potential for variations in penetration rates and growth rates

Six scenarios which consider variations in growth rates of tea production and varying levels of penetration rate of solar based electricity.

3

Sensitivity analysis to the price of solar equipment

Sensitivity analyses using price of solar PV system as a factor on the results of 2 of the six scenarios, scenario 1 and scenario 6. The sensitivity analysis of the remaining 4 is scenarios is presented in the annex.

7.4.1 Results at 100 percent market penetration rate (total addressable market)

Table 50 presents the first set of results that considers 100 percent market penetration, which is equivalent to assuming that all the electricity used in the processing facilities is generated from solar energy. The results suggest that if the country were to reach the 2023/24 target production quantity of tea (46 361 tonnes) using solar based electricity, the total addressable market size would be equivalent to USD 14 million.

Table 50
Market size for Type 2 intervention considering 100 percent penetration rate and government targets

Value chain	Tea
Solar Intervention	Type 2 for tea factory
Target production (2023/24) (t/yr) a	46 361
Annual electricity demand (kWh/tonnes) b	477.5
Unit cost of electricity generated with a solar PV system (USD/kW) c	USD 1767
Market penetration rate	100%
Market Size 2 (USD) d	USD 14 169 951

SOURCE: a. Strategic plan for agriculture transformation 2018-2024. b. Data collected from the field. c. Data collected from the field. d. Estimated by the authors.

This shows that the full market potential for solar based electricity in tea processing facilities could be significant in Rwanda. However, it is unlikely that all the electricity used in the tea processing factories in the country could be completely generated through solar based systems. Additionally, the market potential of the solar technologies would also depend on the actual changes in production quantities of tea and the penetration rate of the specific technology. Furthermore, the market potential of solar PV systems is also sensitive to the cost of the solar PV system which may change in the future. To capture the impact of these changes on the total market potential two steps were taken. The first step was to define six scenarios based on variations in production growth and in the rate of penetration of the solar PV systems. The results for the scenarios are presented in the section 7.2.2. The second step, included in section 7.2.3, was to carry out a sensitivity analysis showing the changes in market potential due to changes in the cost of the solar PV system.

7.4.2 Scenario analysis

Table 4 presents the six scenarios analysed and the corresponding assumptions that were made in the scenarios. The scenarios are a combination of two distinct production growth rates for tea in the country, and three different levels of market penetration rates for solar PV systems at the tea processing factories.

Table 51
Scenario combinations and parameters

Scenario variables

Variables	Low market penetration (LMP)	Medium market penetration (MMP)	High market penetration (HMP)
Low growth of production (LGP)	**Scenario 1** LMP and LGP	**Scenario 3** MMP and LGP	**Scenario 5** HMP and LGP
High growth of production (HGP)	**Scenario 2** LMP and HGP	**Scenario 4** MMP and HGP	**Scenario 6** HMP and HGP

Scenario parameters

Target quantity at Low market growth for tea production	36 866.43 tonnes per year	Assuming a 2.5 percent production growth rate for tea production	
Target quantity at High market growth for tea production	58 758.09 tonnes per year	Assuming a 7.4 percent production growth rate for tea production	
Market penetration rates	Low= 5%	Medium= 50%	High= 75%

SOURCE: Data as outlined in methodological section.

Based on the six scenarios outlined in Table 51, Table 52 presents the market potential corresponding to each scenario. The results suggest that depending on how the production of tea changes over time and the penetration rate of solar PV systems in the country, the market potential of solar PV systems at the processing stage of the tea value chain can range from a minimum of USD 563 400 (LMP and LGP) to a maximum of USD 13 469 283 (HMP and HGP). The complete set of results for scenarios 2–6, is available in Annex I.

Table 52
Market potential of Type 2 intervention in the tea processing stage of the value chain

Value chain	Stage of the value chain	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
		USD	USD	USD	USD	USD	USD
Tea	Tea processing factories	563 400	897 952	5 633 998	8 979 522	8 450 997	13 469 283

SOURCE: Estimations by the authors.

7.4.3 Sensitivity analysis

Sensitivity analysis scenario 1: LMP & LGP

The final step in the analysis is the sensitivity of the market size to the cost of the solar PV system. The analysis was carried out for all market sizes outlined in the scenarios above. Below we report for lower and higher market sizes of the scenarios, namely scenario 1 and scenario 6.

Figure 29 presents the sensitivity analysis of the Type 2 intervention at the processing stage of the tea value chain under scenario 1 (LMP and LGP) to the cost of the solar PV systems. Under the LMP and LGP scenario, the results suggest that the market potential for solar PV systems in the tea processing factory would be USD 563 000 at a price point of USD 2 273 per kW of solar electricity capacity (as listed in the methodology section). However, depending on the change in the cost of solar PV systems, the market size can range from USD 141 000 (at -75 percent of the current price) to USD 986 000 (at +75 percent of the current price).

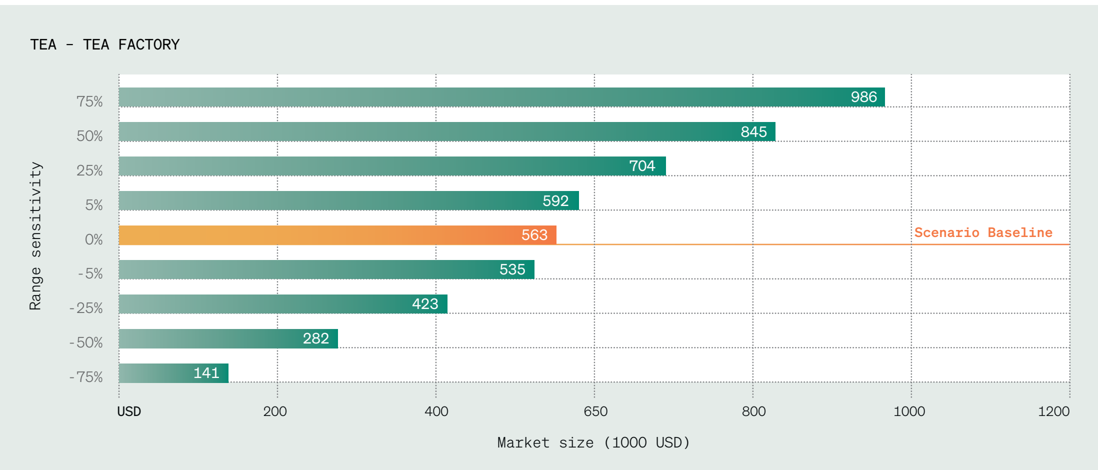

Figure 29
Sensitivity analysis to the cost of solar PV for the market potential under scenario 1

SOURCE: Estimations by the authors.

Figure 30 presents the sensitivity analysis of the Type 2 intervention in the tea value chain in Rwanda under scenario 6 (HMP and HGP). Under the HMP and HGP scenario, the results suggest that the market potential for solar PV systems at tea processing factory would be USD 13 469 283 at a price point of USD 2273 per kW of solar electricity capacity. However, depending on the change in price solar PV systems, the market size can range from USD 3367 000 (at -75 percent of the current price) to USD 23 571 000 (at +75 percent of the current price). The complete set of results for the sensitivity analysis under different scenarios is presented in Annex II.

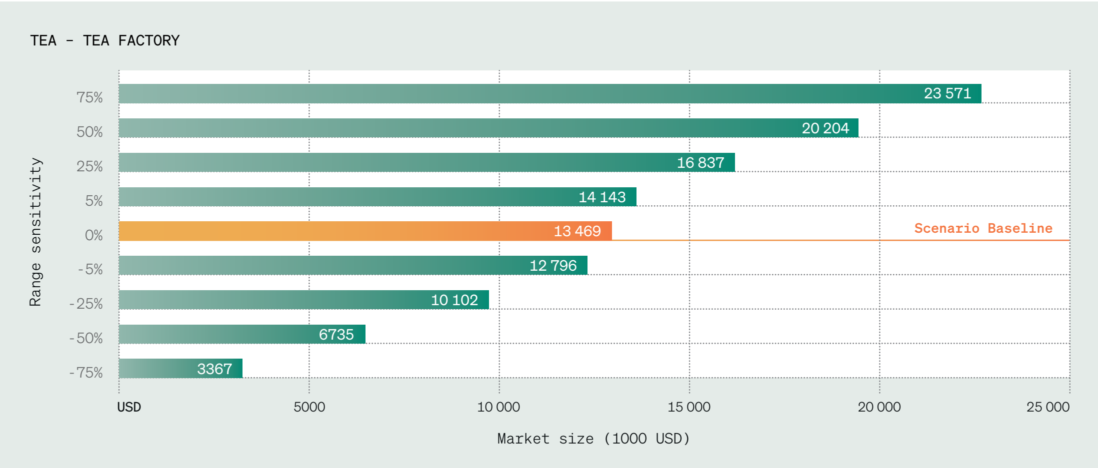

Figure 30
Sensitivity analysis to the cost of solar PV for the market potential under scenario 6

SOURCE: Authors calculations.

Chapter 8
Solar energy in the sugar value chain

8.1 CURRENT SUGAR PRODUCTION AND VALUE CHAIN IN RWANDA

Sugar production in Rwanda is limited and the country's domestic supply relies on one sugar factory – Kabuye Sugar Works. The annual domestic production in the country over the last ten years has fluctuated between 8000 tonnes to 14 000 tonnes. Sugarcane is mostly sourced from 2000 farms along the Nyabarongo River, and it is the main feedstock for sugar production in Rwanda.

The domestic consumption of sugar reached 100 000 tonnes in 2017 with heavy reliance on imports to meet domestic demand. On average, Rwanda produces enough sugar to meet 13 percent of the domestic demand. The remaining domestic sugar consumption is met through imports with annual sugar imports amounting to nearly USD 53 million (IFC, 2019).

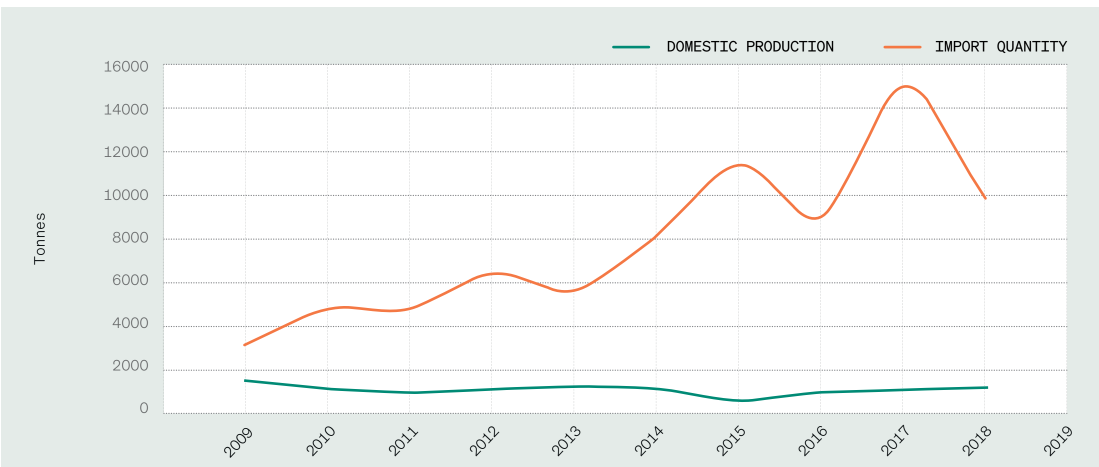

Figure 31
Domestic annual sugar production and imports

SOURCE: FAOSTAT, 2020.

Given the rather limited production of sugar in Rwanda, the sugar value chain is rudimentary and essentially consists of out growers, who supply sugar cane to Kabuye Sugar Works that produces the sugar. Once the sugar cane has reached the sugar factory, sugar cane is crushed to obtain sugar cane juice. The juice is heated and filtered, after which the filtered juice is sent through a series of crystallization steps to create crystals of raw sugar, followed by centrifugation to remove any remaining juice or syrup.

8.2 TARGET SUGAR PRODUCTION IN RWANDA

Given that domestic production of sugar relies on one single factory, the annual output of this facility is equivalent to the annual national output of sugar for the country. The installed production capacity of Kabuye Sugar Works is 14 000 tonnes per year, however, over the past five years the factory has been unable to reach its maximum output. The annual output has fluctuated between 8934 tonnes to 11 466 tonnes. The reason for the low sugar output from the factory is primarily attributed to shortfalls in sugarcane production in the country. In fact, sugarcane is grown along the river Nyabarongo, which is prone to floods that then have a negative impact on the volumes of sugar cane produced which in turn reduces the amount of sugar cane processed in the factory.

Table 53
Annual sugar output from Kabuye Sugar works for the last 5 years

Year	Quantity (Tonnes)
2015 – 2016	11 223
2016 – 2017	10 135
2017 – 2018	11 466
2018 – 2019	8 934
2019 – 2020	10 501

SOURCE: Direct communication with Kabuye Sugar Works.

Due to the fact that only one sugar factory exists in Rwanda, and that the factory is often unable to reach its maximum production capacity given the challenges in sugar cane production, the analysis considers the maximum production capacity of the factory as the target for sugar production by 2024. The assumption is based on the approach of prioritizing full production capacity of the existing factory before further increasing domestic sugar cane production.

8.3. SOLAR INTERVENTION IN SUGAR FACTORIES

Sugar manufacturing is energy intensive and needs both heat and power to transform sugarcane juice into crystal sugar. In addition, sugar production factories often use bagasse, a residue obtained from the sugar cane processing process, to produce energy. This is also the case for Kabuye Sugar Works that produces energy on site using the sugarcane bagasse, in addition to buying electricity from the grid (See Table 54).

Table 54
Energy consumption in Kabuye Sugar Works

Source	Electricity consumption (kWh/month)
Grid	72 000
Own Production (bioenergy using sugarcane bagasse)	400 400

SOURCE: Direct communication with Kabuye Sugar Works.

As a result, given that the electricity generated from bagasse is a form of renewable energy, the analysis focuses specifically on electricity that the factory buys from the national grid. Solar-based equipment would not be applicable in the case of the sugar value chain, therefore, only Type 2 interventions are envisaged for this value chain, see Figure 32. More specifically, the solar energy intervention for this chain entails installing solar PV panels to produce electricity that will replace the electricity the factory currently buys from the national grid. As a result, the sugar factory would be completely powered by a hybrid solar-bioenergy system to supply all its electricity demand.

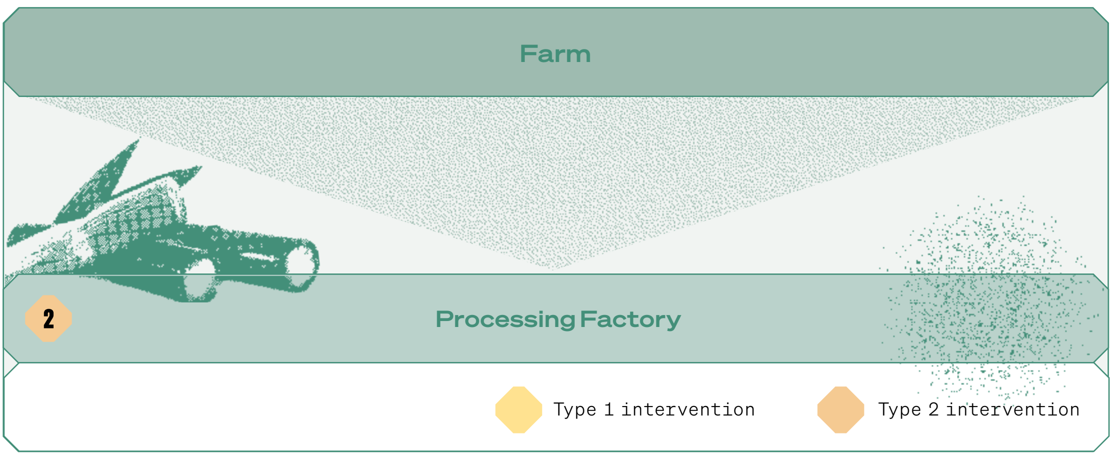

Figure 32
Solar intervention in the sugar value chain

SOURCE: Illustration by the authors.

To estimate the total investment required for installing the solar PV systems, it is necessary to understand the current target sugar production quantity, the cost of solar PV systems in Rwanda and the energy required to produce a tonne of sugar.

Furthermore, given that the annual national sugar output is equivalent to the annual output of Kabuye sugar works, the market size of solar PV systems is essentially related to the total investment required to install solar PV system at Kabuye sugar works. Moreover, considering the fact that Kabuye Sugar Works constantly produces less sugar than its installed capacity of 14 000 tonnes per year, the priority would be to ensure that the current installed capacity be used completely before establishing additional sugar producing factories. Considering this, two scenarios have been analysed:

- the total investment[20] required to install solar PV system to produce current average annual sugar output of the factory (10 452 tonnes/year);
- the total investment required to install solar PV system to reach the maximum production capacity of the Kabuye sugar works (14 000 tonnes/year).

Table 55 details the data obtained from the field work done in Rwanda and through direct communication with the Kabuye Sugar Works.

Table 55
Technical parameters needed to estimate market potential

Parameter	Value
Current sugar production (5-year average, 2015–2020)	10 452 tonnes/year
Target production volume (maximum production capacity of Kabuye sugar works)	14 000 tonnes /year
Grid Electricity need per tonne of sugar produced	7.2 kWh/tonne
Cost of PV system in Rwanda	2273 USD/KW

SOURCE: Fieldwork and direct communication with Kabuye Sugar Works.

20 The market size for solar technology in the case of sugar value chain is equivalent to the investment required to install solar PV system at Kabuye Sugar Works because it is the sole sugar producing factory in Rwanda.

8.4. RESULTS

Table 4 presents the first set of results that take into consideration 100 percent penetration of the identified Type 2 intervention.

Table 56
Market size for the sugar value chains

Parameter	Value (USD)
Total market size of solar PV system at sugar processing stage of the value chain at current production level (10 452 tonnes/ year) and 100 percent penetration.	61 968
Total market size of solar PV system at sugar processing stage of the value chain at target production level (14 000 tonnes/ year) and 100 percent penetration.	83 004

SOURCE: Estimations by the authors.

The results suggest that if the sugar factory were to replace the electricity that is currently supplied by the grid to produce the current production quantity of 10 452 tonnes of sugar by solar PV systems, the market size would be USD 61 968. On the other hand, should the factory realize its maximum sugar production capacity of 14 000 tonnes of sugar per year, and use solar PV to replace the electricity supplied by the grid, the market size would be USD 83 004.

Compared to the other chains analyzed in this report, the market for solar PV technologies in the sugar value chain is rather limited. This is essentially due to the fact that the country currently produces a small amount of sugar domestically and that this production is carried out by one single company. Furthermore, it is important to stress that the market size in this particular case relates to one single company.


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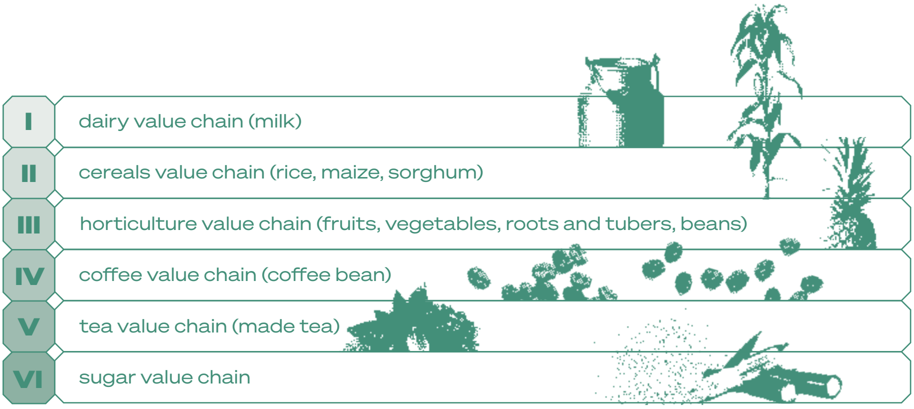
Conclusions

Energy access in Rwanda is still low, but the country has committed to achieving energy access for all by 2030. Agriculture is one of the driving sectors of the economy and contributes around one-third of the country's GDP, employing approximately 70 percent of the working population.

The agriculture sector in Rwanda continues to gain momentum towards achieving its full potential, however, agro-processing is still limited. In fact, the development of a modern agro-processing industry is reliant on the availability and access to reliable and affordable electricity required to run processing equipment, and cold storages, for example. One channel through which value chains could be further developed in Rwanda is access to energy and energy alternatives. Solar-powered equipment and solar-based electricity are some of the solutions that might enable the transition to a less fossil fuel intensive agricultural production system. However, this requires understanding which solar energy solutions are viable, while considering the specific context and needs of the country. The analysis presented provides the first broad estimate of existing opportunities within the agri-food chains in Rwanda.

As a first step, the relevant agri-food chains were identified. Given the range of agricultural products produced in the country, the stages of each value chain group, the possibilities for solar energy use and update, the various crops and commodities produced were grouped into the following value chain groups and analysed by group:



Solar interventions are differentiated in two types: solar-powered equipment (Type 1) and solar-generated electricity (Type 2). The value chains are qualified by stages of production and processing and the exact type of solar intervention is specified at each step of the value chain. For each one of these groupings, the full market potential (considering a potential target production volume and full market penetration) is assessed for both Type 1 and Type 2 interventions. Scenarios are run to cater for potential fluctuations in agriculture production and for differences in market penetration rates. The final step is to account for variations in prices.

The results show that there is considerable market potential throughout the value chains. For milk, when considering solar-based equipment, the largest market potential is found at the farm level, around USD 25 million, followed by interventions at the simple milk collection level and at the modern milk collection centres. The market for solar-based electricity, is the largest in the case of skimmed milk powder and UHT milk, which are around USD 13 million each, followed by pasteurized milk. Growth rates, market penetration rates and prices all have an impact on the potential market size, reducing the overall volume of the market.

Within the horticulture sector the potential market size for cold storage is considerable, reaching a full market potential of more than USD 470 million. This market size is an indicator of the considerable level of development that would be required to increase the cooling capacity per capita in the country. Given the limited juice-processing capacity in the country, the potential market for Type 2 interventions is considerably smaller, reaching just over USD 140 000.

Coffee is mostly exported, with some milling and very limited roasting taking place in the country. Given the structure of the chain, solar interventions in this case are mainly limited to solar-based electricity generation. The largest market potential is found at the coffee washing stations with a maximum market potential of USD 3 million

The cereals sector, including rice, has a significant market potential in terms of solar equipment and solar-based electricity. Solar-based equipment could reach a total market potential of more than USD 20 million in the rice value chain and just under USD 40 million in the cereals value chain. Solar-based electricity could reach a full market potential of USD 1.5 million in rice and USD 5.2 million in cereals.

For the tea and sugar value chains only Type 2 interventions at the processing level are feasible as no solar-based equipment currently exists on the market. In the case of tea, the potential market size for Type 2 solar interventions is substantial, reaching around USD 13 million. In the case of sugar, given that domestic sugar production is small, the potential market size for Type 2 interventions could reach a maximum of USD 83 000.

In conclusion, the analysis highlights the areas with the highest market potential, that could represent a first entry point for solar-based interventions in Rwanda. These identified solar-based interventions can be a specific channel to stimulate agriculture productivity, by enabling access to sustainable alternative energy resources. In particular, Type 1 solar energy interventions in horticulture, milk and the cereal value chains seem especially promising. They could furthermore solve some of the structural constraints to the deployment of a modern agribusiness sector and potentially have a larger social impact (job creation, poverty reduction, new business development). As explained at the onset of the analysis, the specific focus was on an initial identification of the theoretical solar energy market potential. When considering this option in detail, a full analysis would be required. Furthermore, solar energy solutions need to be considered within a full energy mix assessment and compared against other renewable energy solutions, in order to find the best sustainable and cost-effective energy solutions for the agri-food chain.

References

Batidzirai, B., Moyo, A. & Kapembwa, M. 2018. *Willingness to pay for improved electricity supply reliability in Zambia A survey of urban enterprises in Lusaka and Kitwe.*

Beech, G.A. & Crafts-Lighty, A.L. 1980. *Energy use in flour production.* Journal of the Science of Food and Agriculture, 31(8): 830–838. https://doi.org/10.1002/jsfa.2740310813.

CBI. 2018. *Value Chain Analysis for the Coffee Sector in Rwanda.*

CFI. 2019. *Total Addressable Market - Learn How to Calculate the TAM* [online].

FAO. 2016. *Country situation and role of agriculture: Rwanda*. Available online at http://www.fao.org/3/a-i5900e.pdf.

FAO. 2018. *FAOSTAT* [online]. http://www.fao.org/faostat/en/#home.

Flammini, A., Bracco, S., Sims, R., Cooke, J. & Elia, A. 2018. *Costs and Benefits of Clean Energy Technologies in the Milk, Vegetable and Rice Value Chains INTERVENTION LEVEL.* Rome, Italy, Food and Agriculture Organization of the United Nations. 268 pp.

Foster, C. & Graham,M. 2015. *Connectivity and the Tea Sector in Rwanda Value Chains and Networks of Connectivity-Based Enterprises in Rwanda.* Available online at https://opendocs.ids.ac.uk/opendocs/bitstream/handle/20.500.12413/11951/Connectivity_and_the_Tea_Sector_in_Rwanda.pdf?sequence=1&isAllowed=y.

Ghins, L. & Pauw, K. 2018. *The impact of markets and policy on incentives for rice production in Rwanda.* FAO AGRICULTURAL DEVELOPMENT ECONOMICS WORKING PAPER, 02: 1–36.

Government of Rwanda. 2014. *National Horticulture Policy and Strategic Implimentation Plan.* (September): 1–76.

Government of Rwanda. 2018. *Strategic plan for agriculture transformation.*

Goyal, S.K., Jogdand, S. V. & Agrawal, A.K. 2012. *Energy use pattern in rice milling industries—a critical appraisal.* Journal of Food Science and Technology, 51(11): 2907–2916. https://doi.org/10.1007/s13197-012-0747-3.

Grimm, M., Lenz, L., Peters, J. & Sievert, M. 2016. *Demand for Off-Grid Solar Electricity: Experimental Evidence from Rwanda.* IZA – Institute of Labor Economics Discussion papers (10427): 35.

Habes, J.G. 2017. *Sugarcane harvest scheduling in Rwanda.* Wageningen University and Research Centre.

IFAD. 2016. *Rwanda dairy development project: Detailed design report.* (also available at https://webapps.ifad.org/members/eb/118/docs/EB-2016-118-R-19-Project-design-report.pdf).

International Finance Corporation (IFC). 2019. *Creating Markets in Rwanda: Transforming for the Jobs of Tomorrow.*
IGC. 2017. *Maize value chains in East Africa.*
ILO. 2019. *Employment in Export-Oriented Agricultural Value Chain in Rwanda.* Available online at https://www.ilo.org/wcmsp5/groups/public/---ed_emp/---ifp_skills/documents/publication/wcms_723288.pdf.
Kotler, P., Wong, V., Saunders, J. & Armstrong, G. 2001. *Principles of marketing: Third European edition.* xxiii, 1031 p. (also available at https://journals.co.za/content/mfsa/11/3/EJC75657).
KPMG. 2014. *Industrial Master Plan for the Agro-Processing Subsector* (2014–2020) Ministry of Trade and Industry (MINICOM). Kigali, Rwanda. 114 pp.
MINAGRI. 2014. Baseline Report on the Rwanda Horticulture Organisations Survey.
MINAGRI. 2018. *National Strategic Plan for Agriculture Transformation 2018–2024*. Kigali, Rwanda. 235 pp.
Mwizerwa, C. & Kayitare, P.Y. 2018. *Rwanda economy expanded by 6.7% in Q2 2018* | National Institute of Statistics Rwanda. In: Statistics Article [online].
Shapiro, B.I., Gebru, G., Desta, S. & Nigussie, K. 2017. *Rwanda Livestock Master Plan Developed by the International Livestock Research Institute (ILRI) Livestock Master Plan (LMP) team*. 124 pp.
Singh, R. 2015. Hybrid Membrane Systems–Applications and Case Studies. In *Membrane Technology and Engineering for Water Purification (Second Edition)*, pp. 179 & 281. Elsevier Science & Technology Books.
TECHNOSERVE. 2018. *Financing Opportunities in Rwanda's Coffee Sector.* Kigali, Rwanda. 26 pp.
Tuszyński, W., Diakowska, E.A.A. & Hall, N.S. 1983. *Solar energy in small-scale milk collection and processing.* Rome, Italy, Food and Agriculture Organization of the United Nations. 116 pp.
UNIDO. 2013. *Maize in Rwanda : A Value Chain Analysis.*
USAID. 2018. *Postharvest Loss Assessment of Tomatoes in Rwanda.* (also available at https://horticulture.ucdavis.edu/information/postharvest-loss-assessment-orange-fleshed-sweet-potatoes-rwanda).
Waheed, M. A., Jekayinfa, S.O., Ojediran, J.O. & Imeokparia, O.E. 2008. *Energetic analysis of fruit juice processing operations in Nigeria.* Energy, 33(1): 35–45. https://doi.org/10.1016/j.energy.2007.09.001.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Annex I
Additional results for scenarios 1 to 6

DAIRY VALUE CHAIN (MILK)

Results Type 1

Value chain	PV + equipment	Current milk processing capacity	Qe (tonnes/yr)	Fraction processed (%)	Price of equipment (USD)
Milk	Farm level cooling	64 400	4.6	100%	515
Milk	Simple milk collection	64 400	37.95	100%	1699
Milk	Modern milk collection	64 400	575	100%	8900

		Baseline		
Value chain	PV + equipment	Number of units of equipment	MPR (%)	Project milk processing capacity (Qp) (t/yr)
Milk	Farm level cooling	47 750	100%	219 650
Milk	Simple milk collection	578	100%	219 650
Milk	Modern milk collection	382	100%	219 650

Results Type 2

Value chain	PV + equipment	Current milk processing capacity	Ed = Annual electricity demand (kWh/tonnes)	Cpv = unit cost of unit of electricity generated with a solar PV sustem (USD/kW)
Milk	Pasteurized milk	64 400	50	2237
Milk	UHT mik in containers	64 400	90	1767
Milk	Skim milk powder	64 400	90	1767

		Baseline	
Value chain	PV + equipment	MPR (%)	Project milk processing capacity (Qp) (t/yr)
Milk	Pasteurized milk	100%	219 650
Milk	UHT mik in containers	100%	219 650
Milk	Skim milk powder	100%	219 650

Scenario 1			Scenario 2			Scenario 3		
Number of units of equipment	MPR (%)	Project milk processing capacity (Qp) (t/yr)	Number of units of equipment	MPR (%)	Project milk processing capacity (Qp) (t/yr)	Number of units of equipment	MPR (%)	Project milk processing capacity (Qp) (t/yr)
15 840	5%	72 863	19 998	5%	91 986	15 840	50%	72 863
1920	5%	72 863	2424	5%	91 986	1920	50%	72 863
127	5%	72 863	160	5%	91 986	127	50%	72 863

Scenario 4			Scenario 5			Scenario 6		
Number of units of equipment	MPR (%)	Project milk processing capacity (Qp) (t/yr)	Number of units of equipment	MPR (%)	Project milk processing capacity (Qp) (t/yr)	Number of units of equipment	MPR (%)	Project milk processing capacity (Qp) (t/yr)
19 998	50%	91 986	15 840	75%	72 863	19 998	75%	91 986
2424	50%	91 986	1920	75%	72 863	2424	75%	91 986
160	50%	91 986	127	75%	72 863	160	75%	91 986

Scenario 1		Scenario 2		Scenario 3	
MPR (%)	Project milk processing capacity (Qp) (t/yr)	MPR (%)	Project milk processing capacity (Qp) (t/yr)	MPR (%)	Project milk processing capacity (Qp) (t/yr)
5%	82 437	5%	131 390	50%	82 437
5%	82 437	5%	131 390	50%	82 437
5%	82 437	5%	131 390	50%	82 437

Scenario 4		Scenario 5		Scenario 6	
MPR (%)	Project milk processing capacity (Qp) (t/yr)	MPR (%)	Project milk processing capacity (Qp) (t/yr)	MPR (%)	Project milk processing capacity (Qp) (t/yr)
50%	131 390	75%	82 437	75%	131 390
50%	131 390	75%	82 437	75%	131 390
50%	131 390	75%	82 437	75%	131 390

CEREALS VALUE CHAIN (RICE, MAIZE, SORGHUM)

Results Type 1

Value chain	PV + equipment	Current cereals processing capacity	Qe (tonnes/yr)	Fraction processed (%)	Price of equipment (USD)
Rice	Soar husker + polisher	43 506	18.8125	100%	4850
Cereals	Solar milk (small scale)	186 024	27.95	100%	3650

		Baseline		
Value chain	PV + equipment	Number of units of equipment	MPR (%)	Project cereals processing capacity (Qp) (t/yr)
Rice	Soar husker + polisher	4248	100%	79 913
Cereals	Solar milk (small scale)	10 942	100%	305 804

Results Type 2

Value chain	PV + equipment	Current milk processing capacity	Ed = Anual electricity demand (kWh/tonnes)	Cpv = unit cost of unit of electricity generated with a solar PV sustem (USD/kW)
Rice	Rice mill	24 170	52.8	1767
Cereals	Cereals mill	217 028	23.0	1767

		Baseline	
Value chain	PV + equipment	MPR (%)	Project cereals processing capacity (Qp) (t/yr)
Rice	Rice mill	100%	32 575
Cereals	Cereals mill	100%	254 836

Scenario 1			Scenario 2			Scenario 3		
Number of units of equipment	MPR (%)	Project cereals processing capacity (Qp) (t/yr)	Number of units of equipment	MPR (%)	Project cereals processing capacity (Qp) (t/yr)	Number of units of equipment	MPR (%)	Project cereals processing capacity (Qp) (t/yr)
2617	5%	49 224	3304	5%	62 143	2617	50%	49 224
7531	5%	210 469	9507	5%	265 709	7531	50%	210 469

Scenario 4			Scenario 5			Scenario 6		
Number of units of equipment	MPR (%)	Project cereals processing capacity (Qp) (t/yr)	Number of units of equipment	MPR (%)	Project cereals processing capacity (Qp) (t/yr)	Number of units of equipment	MPR (%)	Project cereals processing capacity (Qp) (t/yr)
3304	50%	62 143	2617	75%	49 224	3304	75%	62 143
9507	50%	265 709	7531	75%	210 469	9507	75%	265 709

Scenario 1		Scenario 2		Scenario 3	
MPR (%)	Project cereals processing capacity (Qp) (t/yr)	MPR (%)	Project cereals processing capacity (Qp) (t/yr)	MPR (%)	Project cereals processing capacity (Qp) (t/yr)
5%	30 940	5%	49 312	50%	30 940
5%	277 814	5%	316 274	50%	277 814

Scenario 4		Scenario 5		Scenario 6	
MPR (%)	Project cereals processing capacity (Qp) (t/yr)	MPR (%)	Project cereals processing capacity (Qp) (t/yr)	MPR (%)	Project cereals processing capacity (Qp) (t/yr)
50%	49 312	75%	30 940	75%	49 312
50%	316 274	75%	277 814	75%	316 274

HORTICULTURE VALUE CHAIN (FRUITS, VEGETABLES, ROOTS AND TUBERS, BEANS)

Results Type 1

Value chain	PV + equipment	Current horticulture processing capacity	Qe (tonnes/yr)	Fraction processed (%)	Price of equipment (USD)
Horticulture	Cold storage capacity required for export target only	42 445	164.25	100%	22 000
Horticulture	Cold storage capacity to store 50% of horticulutre products produced in 2024	2 953 681	164.25	100%	22 000

		Baseline		
Value chain	PV + equipment	Number of units of equipment	MPR (%)	Project horticulture processing capacity (Qp) (t/yr)
Horticulture	Cold storage capacity required for export target only	282	100%	46 314
Horticulture	Cold storage capacity to store 50% of horticulutre products produced in 2024	21 376	100%	3 510 998

Results Type 2

Value chain	PV + equipment	Current horticulture processing capacity	Ed = Annual electricity demand (kWh/tonnes)	Cpv = unit cost of unit of electricity generated with a solar PV sustem (USD/kW)
Horticulture	Fruit juice	2563	57.6	1767

		Baseline	
Value chain	PV + equipment	MPR (%)	Project horticulture processing capacity (Qp) (t/yr)
Horticulture	Fruit juice	100%	32 575

Scenario 1			Scenario 2			Scenario 3		
Number of units of equipment	MPR (%)	Project horticulture processing capacity (Qp) (t/yr)	Number of units of equipment	MPR (%)	Project horticulture processing capacity (Qp) (t/yr)	Number of units of equipment	MPR (%)	Project horticulture processing capacity (Qp) (t/yr)
293	5%	48 023	370	5%	60 627	293	50%	48 023
20 346	5%	3 341 819	25 686	5%	4 218 919	20 346	50%	3 341 819

Scenario 4			Scenario 5			Scenario 6		
Number of units of equipment	MPR (%)	Project horticulture processing capacity (Qp) (t/yr)	Number of units of equipment	MPR (%)	Project horticulture processing capacity (Qp) (t/yr)	Number of units of equipment	MPR (%)	Project horticulture processing capacity (Qp) (t/yr)
370	50%	60 627	293	75%	48 023	370	75%	60 627
25 686	50%	4 218 919	20346	75%	3 341 819	25686	75%	4 218 919

Scenario 1		Scenario 2		Scenario 3	
MPR (%)	Project horticulture processing capacity (Qp) (t/yr)	MPR (%)	Project horticulture processing capacity (Qp) (t/yr)	MPR (%)	Project horticulture processing capacity (Qp) (t/yr)
5%	5228	5%	3280	50%	5228

Scenario 4		Scenario 5		Scenario 6	
MPR (%)	Project horticulture processing capacity (Qp) (t/yr)	MPR (%)	Project horticulture processing capacity (Qp) (t/yr)	MPR (%)	Project horticulture processing capacity (Qp) (t/yr)
50%	3280	75%	5228	75%	3280

COFFEE VALUE CHAIN (COFFEE BEAN)

Results Type 2

Value chain	PV + equipment	Current coffee processing capacity	Ed = Annual electricity demand (kWh/tonnes)	Cpv = unit cost of unit of electricity generated with a solar PV sustem (USD/kW)
Coffee	Washing station (CWS)	69 461	39.7	2273
Coffee	Dry mills	13 892	31.4	1767
Coffee	Roasters	5557	40.0	1767

		Baseline	
Value chain	PV + equipment	MPR (%)	Project coffee processing capacity (Qp) (t/yr)
Coffee	Washing station (CWS)	100%	96 215
Coffee	Dry mills	100%	18 523
Coffee	Roasters	100%	7409

TEA VALUE CHAIN

Results Type 2

Value chain	PV + equipment	Current processing capacity	Ed = Annual electricity demand (kWh/tonnes)	Cpv = unit cost of unit of electricity generated with a solar PV sustem (USD/kW)
Tea	Processing	28 000	478	1767

		Baseline	
Value chain	PV + equipment	MPR (%)	Target processing capacity (Qp) (t/yr)
Tea	Processing	100%	46 361

Scenario 1		Scenario 2		Scenario 3	
MPR (%)	Project coffee processing capacity (Qp) (t/yr)	MPR (%)	Project coffee processing capacity (Qp) (t/yr)	MPR (%)	Project coffee processing capacity (Qp) (t/yr)
5%	88 917	5%	141 716	50%	88 917
5%	17 783	5%	28 343	50%	17 783
5%	7113	5%	11 337	50%	7113

Scenario 4		Scenario 5		Scenario 6	
MPR (%)	Project coffee processing capacity (Qp) (t/yr)	MPR (%)	Project coffee processing capacity (Qp) (t/yr)	MPR (%)	Project coffee processing capacity (Qp) (t/yr)
50%	141 716	75%	88 917	75%	141 716
50%	28 343	75%	17 783	75%	28 343
50%	11 337	75%	7113	75%	11 337

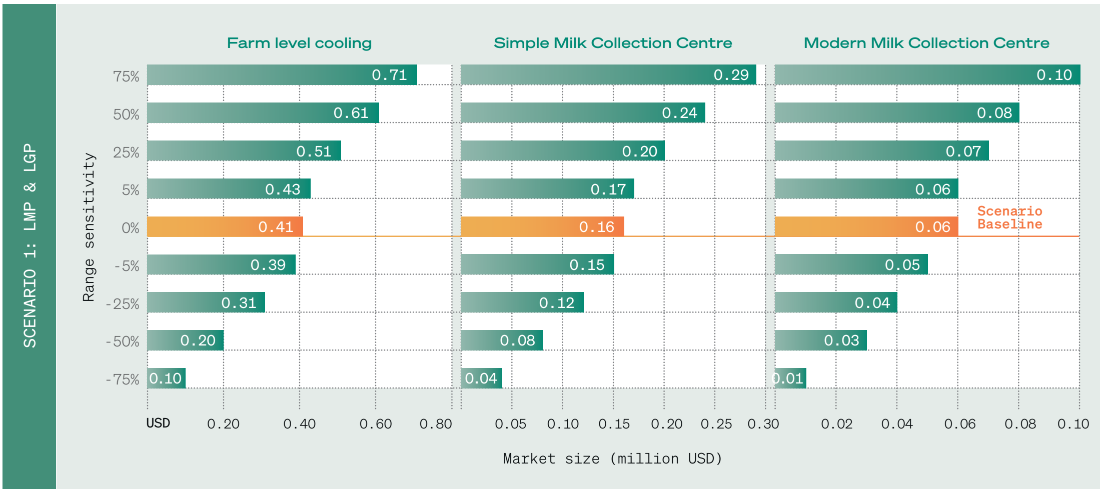
Scenario 1		Scenario 2		Scenario 3	
MPR (%)	Target processing capacity (Qp) (t/yr)	MPR (%)	Target processing capacity (Qp) (t/yr)	MPR (%)	Target processing capacity (Qp) (t/yr)
5%	36 866	5%	58 758	50%	36 866

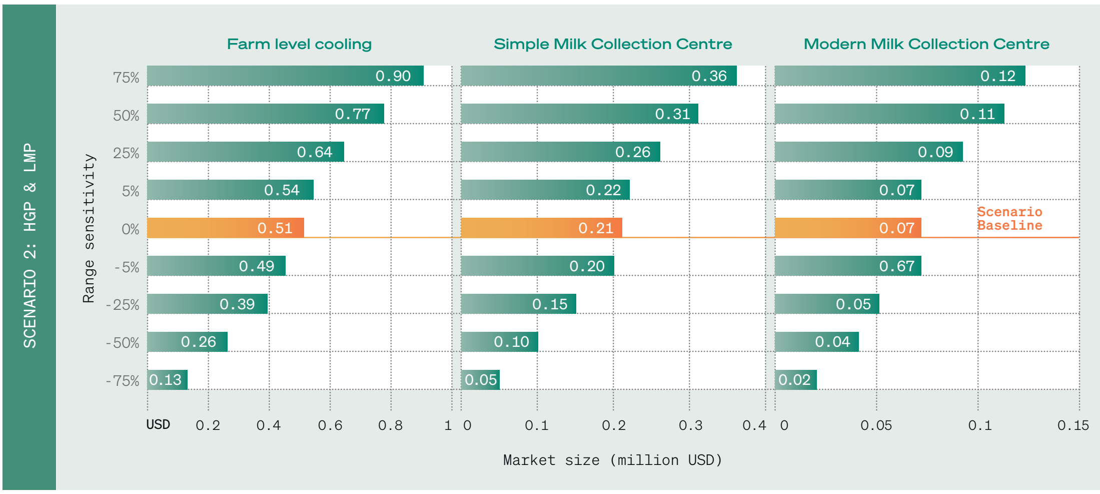
Scenario 4		Scenario 5		Scenario 6	
MPR (%)	Target processing capacity (Qp) (t/yr)	MPR (%)	Target processing capacity (Qp) (t/yr)	MPR (%)	Target processing capacity (Qp) (t/yr)
50%	58 758	75%	36 866	75%	58 758

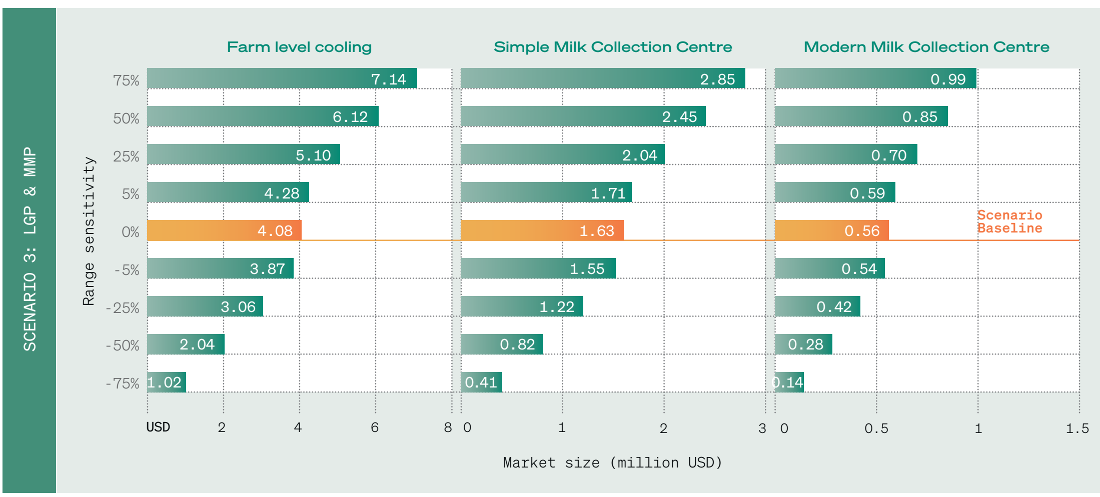
Annex II
Additional results for sensitivities in scenarios 1 to 6

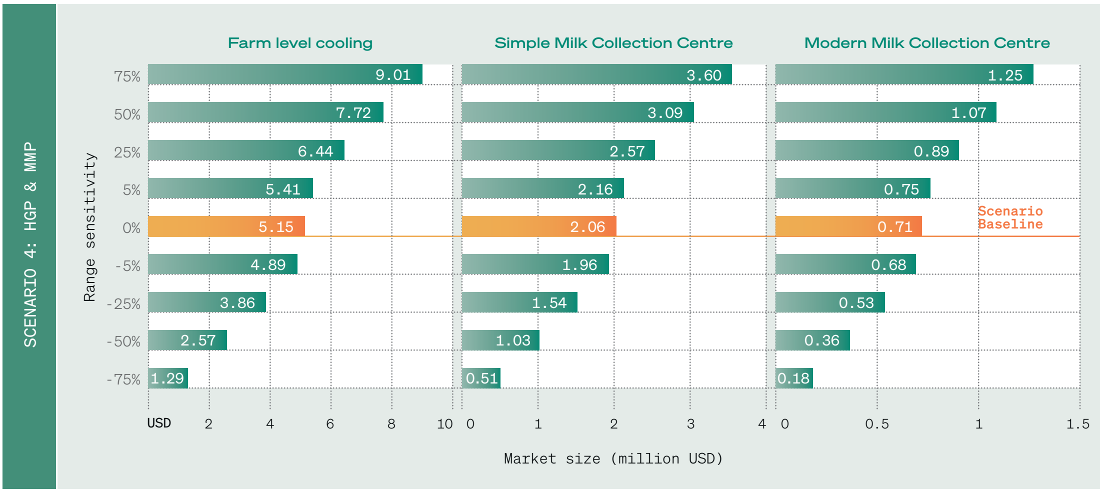
DAIRY VALUE CHAIN (MILK)

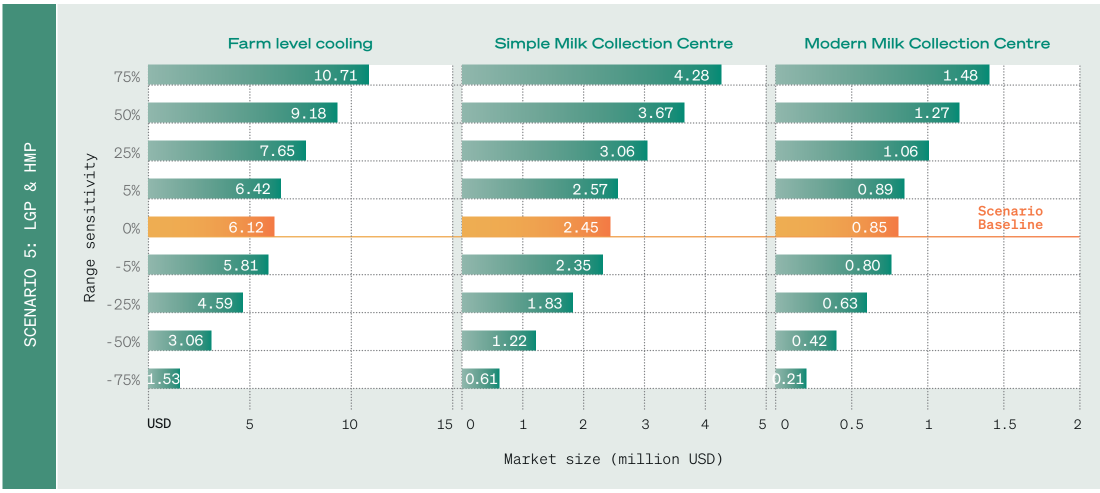
Results type 1

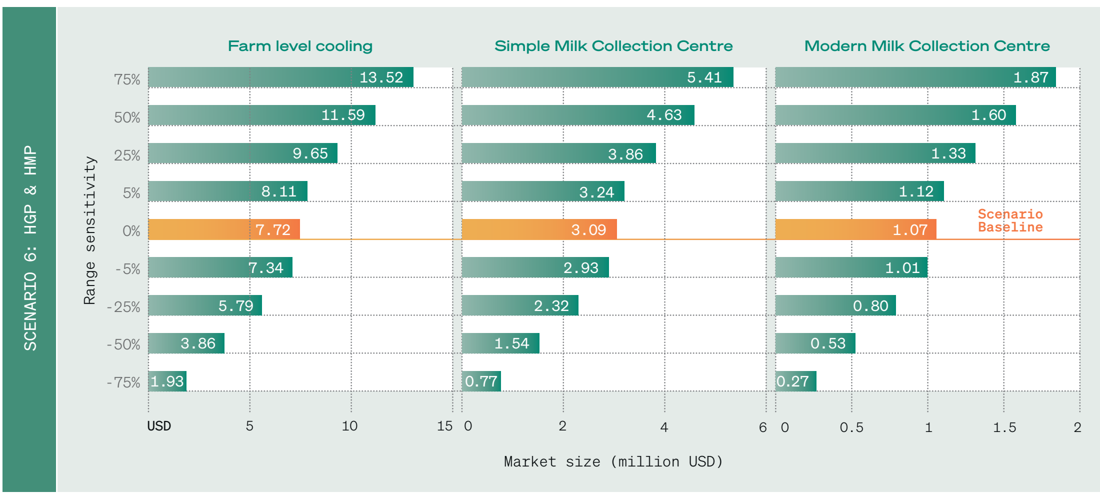




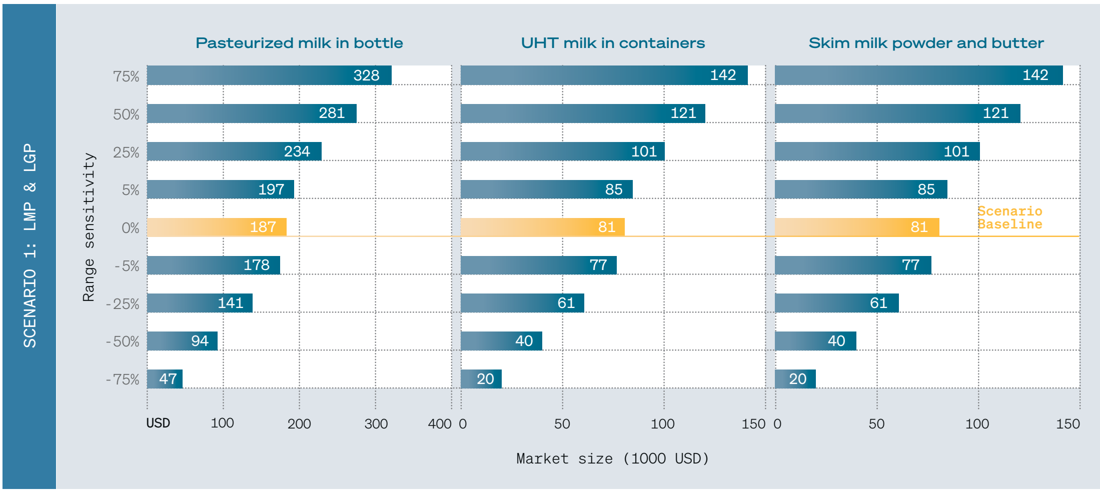


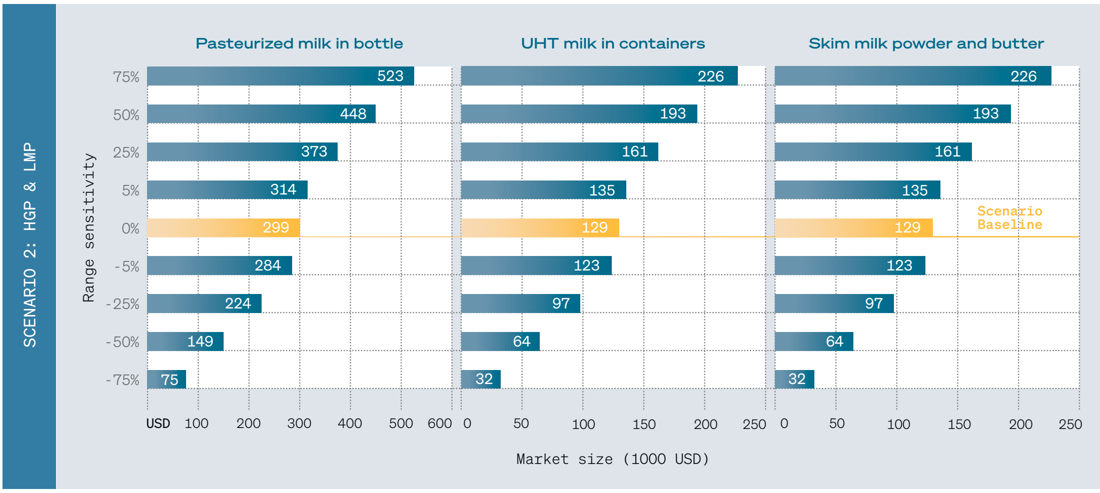

SCENARIO 4: HGP & MMP
Range sensitivity
Farm level cooling
Simple Milk Collection Centre
Modern Milk Collection Centre
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
9.01
7.72
6.44
5.41
5.15
4.89
3.86
2.57
1.29
3.60
3.09
2.57
2.16
2.06
1.96
1.54
1.03
0.51
1.25
1.07
0.89
0.75
0.71
0.68
0.53
0.36
0.18
Scenario Baseline
USD
2
4
6
8
10
0
1
2
3
4
0
0.5
1
1.5
Market size (million USD)

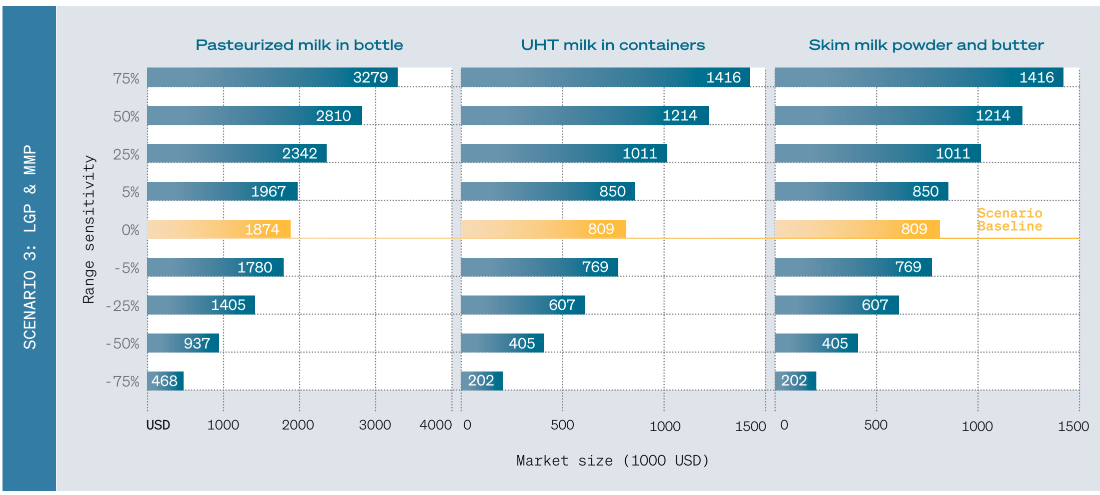

SCENARIO 5: LGP & HMP
Range sensitivity
Farm level cooling
Simple Milk Collection Centre
Modern Milk Collection Centre
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
10.71
9.18
7.65
6.42
6.12
5.81
4.59
3.06
1.53
4.28
3.67
3.06
2.57
2.45
2.35
1.83
1.22
0.61
1.48
1.27
1.06
0.89
0.85
0.80
0.63
0.42
0.21
Scenario Baseline
USD
5
10
15
0
1
2
3
4
5
0
0.5
1
1.5
2
Market size (million USD)

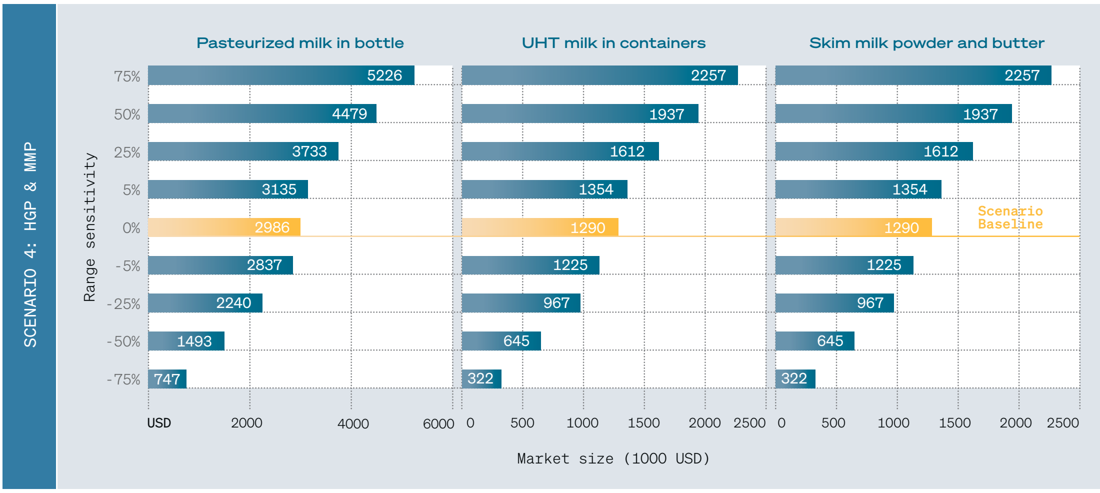

SCENARIO 6: HGP & HMP
Range sensitivity
Farm level cooling
Simple Milk Collection Centre
Modern Milk Collection Centre
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
13.52
11.59
9.65
8.11
7.72
7.34
5.79
3.86
1.93
5.41
4.63
3.86
3.24
3.09
2.93
2.32
1.54
0.77
1.87
1.60
1.33
1.12
1.07
1.01
0.80
0.53
0.27
Scenario Baseline
USD
5
10
15
0
2
4
6
0
0.5
1
1.5
2
Market size (million USD)

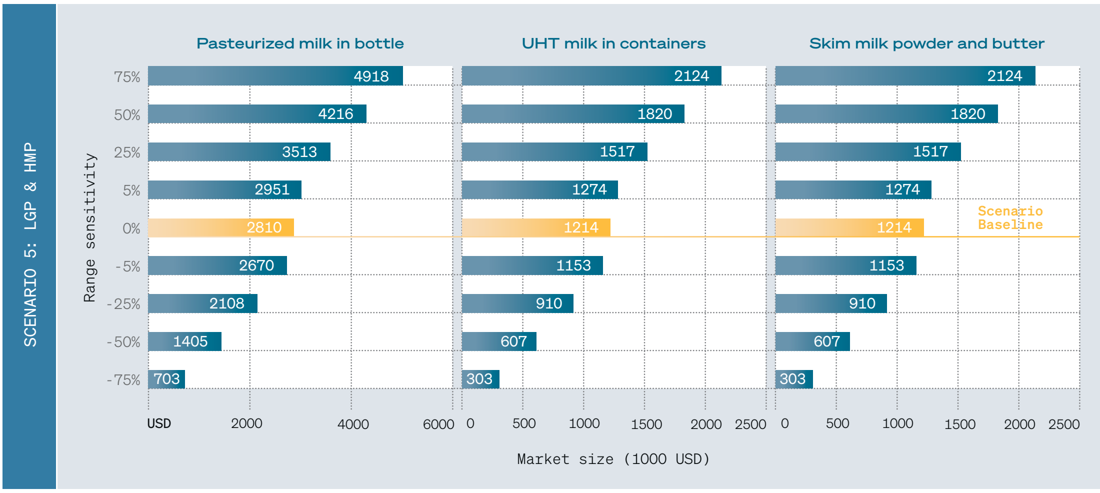
Results type 2

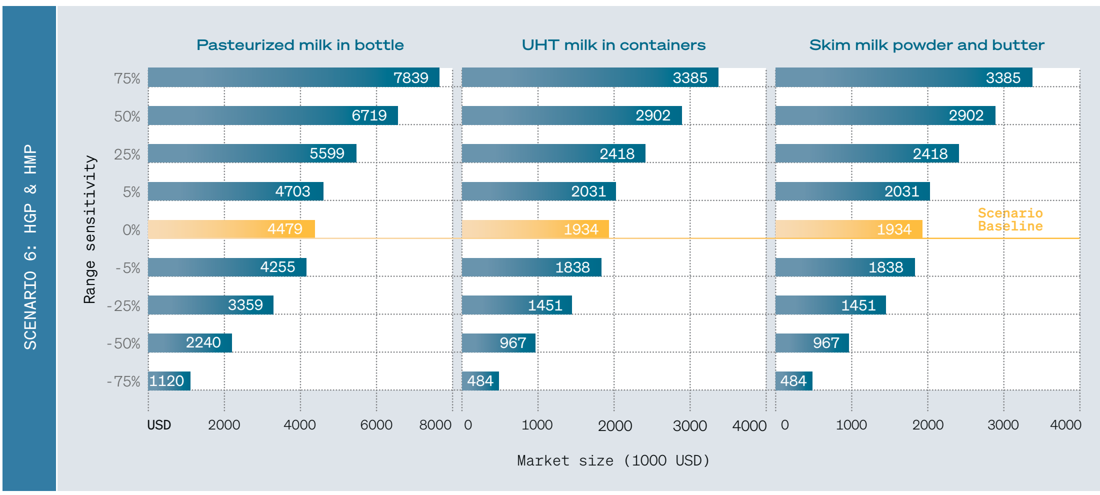




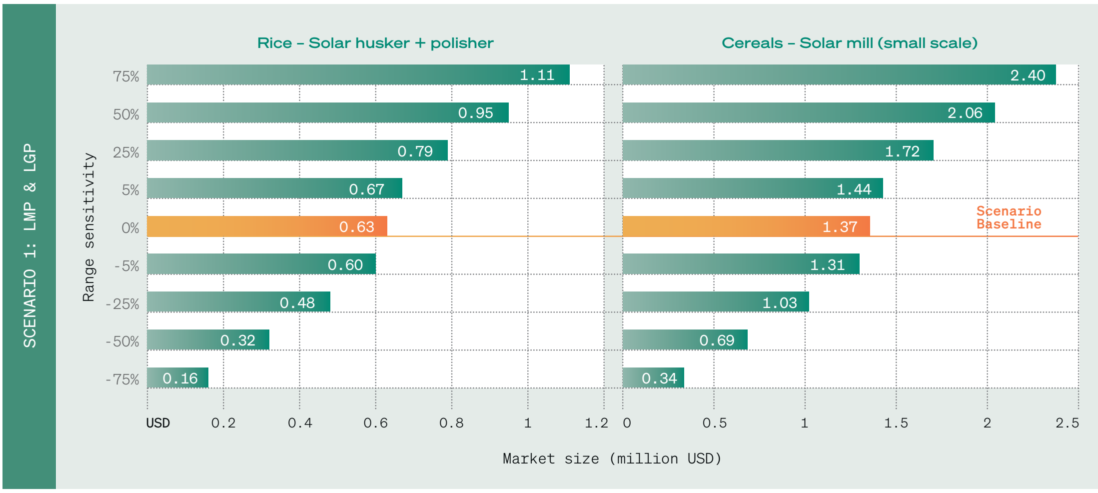


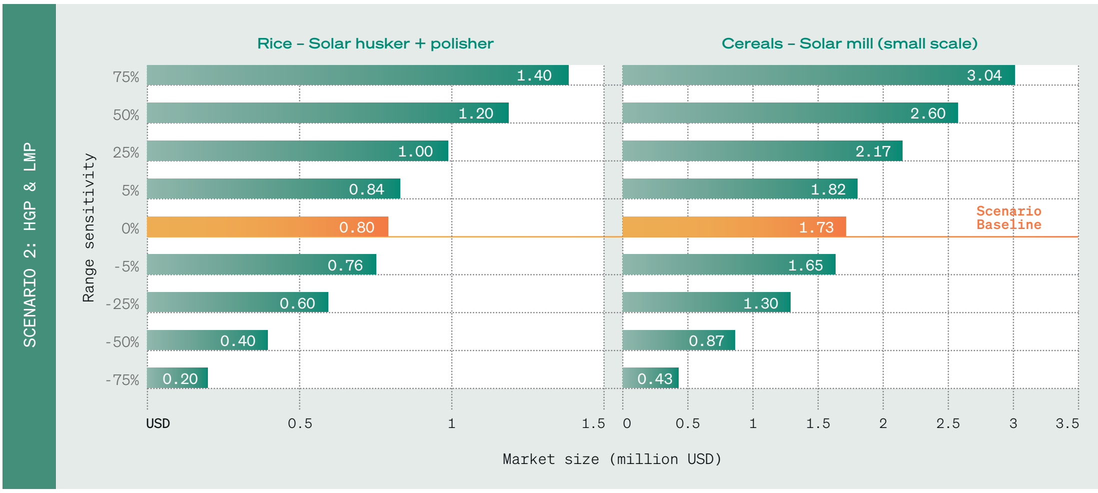

SCENARIO 4: HGP & MMP
Range sensitivity
Pasteurized milk in bottle
UHT milk in containers
Skim milk powder and butter
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
5226
4479
3733
3135
2986
2837
2240
1493
747
2257
1937
1612
1354
1290
1225
967
645
322
2257
1937
1612
1354
1290
1225
967
645
322
Scenario Baseline
USD
2000
4000
6000
0
500
1000
1500
2000
2500
0
500
1000
1500
2000
2500
Market size (1000 USD)

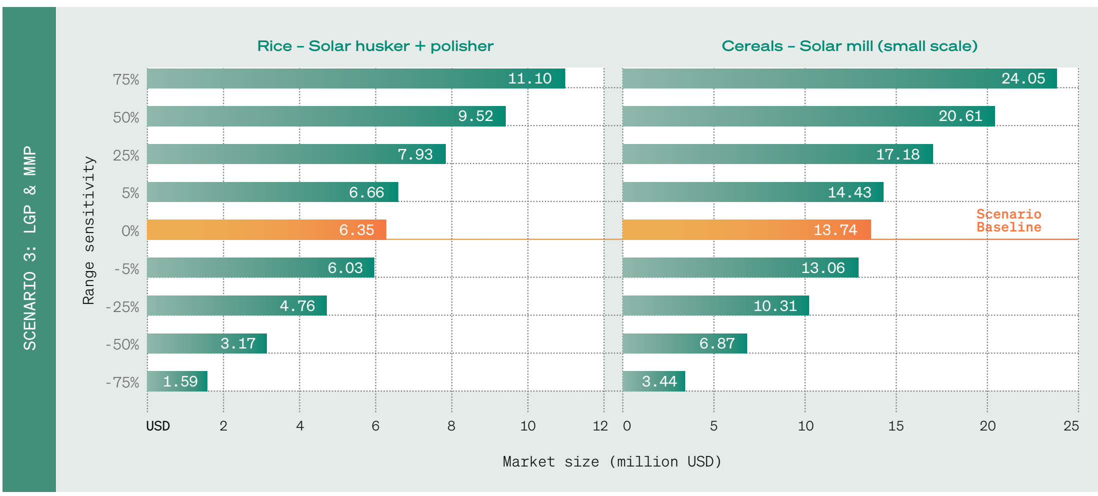

SCENARIO 5: LGP & HMP
Range sensitivity
Pasteurized milk in bottle
UHT milk in containers
Skim milk powder and butter
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
4918
4216
3513
2951
2810
2670
2108
1405
703
2124
1820
1517
1274
1214
1153
910
607
303
2124
1820
1517
1274
1214
1153
910
607
303
Scenario Baseline
USD
2000
4000
6000
0
500
1000
1500
2000
2500
0
500
1000
1500
2000
2500
Market size (1000 USD)

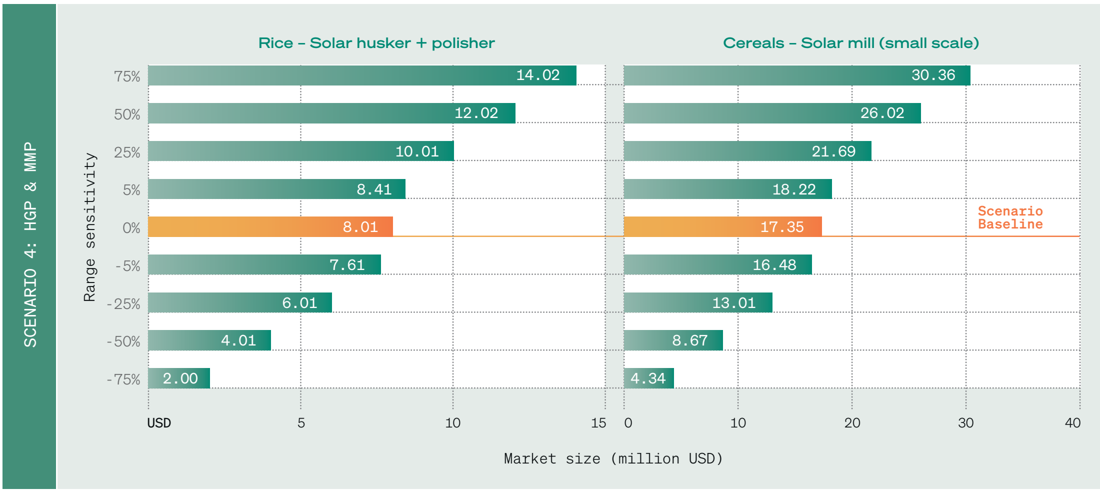

SCENARIO 6: HGP & HMP
Range sensitivity
Pasteurized milk in bottle
UHT milk in containers
Skim milk powder and butter
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
7839
6719
5599
4703
4479
4255
3359
2240
1120
3385
2902
2418
2031
1934
1838
1451
967
484
3385
2902
2418
2031
1934
1838
1451
967
484
Scenario Baseline
USD
2000
4000
6000
8000
0
1000
2000
3000
4000
0
1000
2000
3000
4000
Market size (1000 USD)

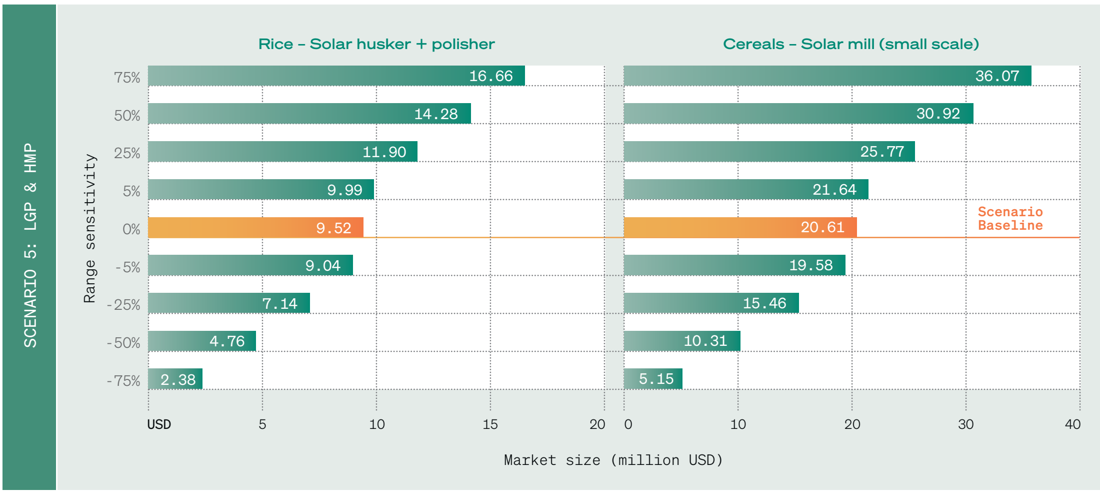
Results type 1

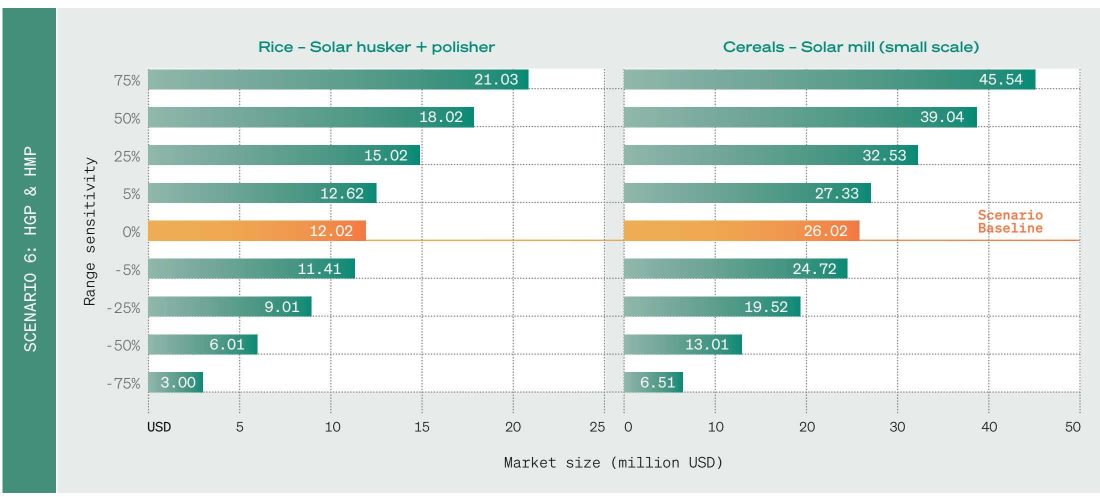




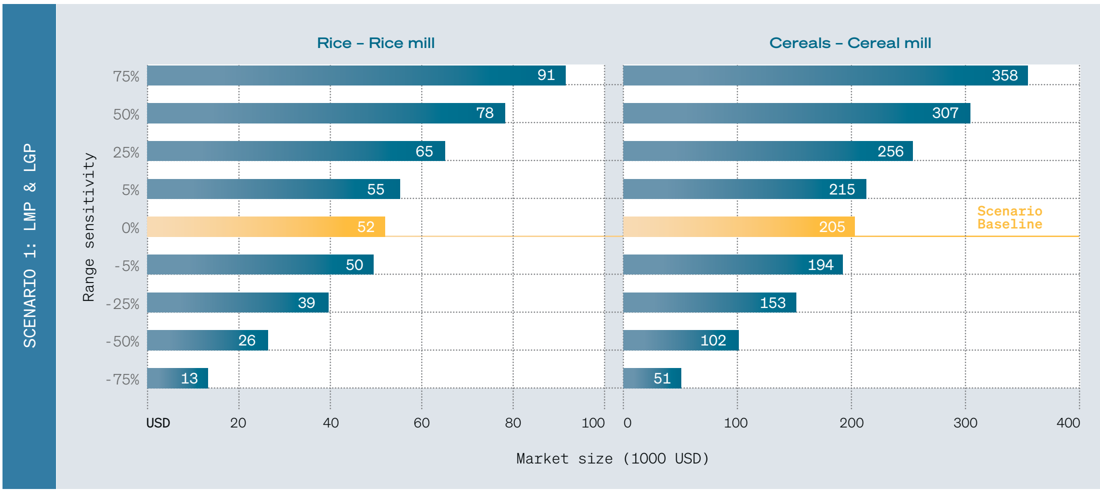


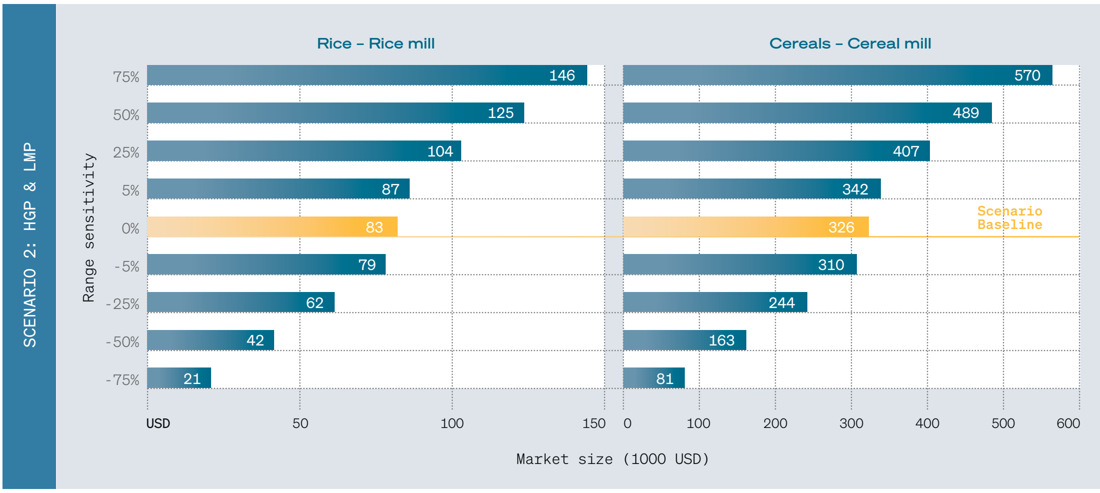

SCENARIO 4: HGP & MMP
Range sensitivity
Rice – Solar husker + polisher
Cereals – Solar mill (small scale)
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
14.02
12.02
10.01
8.41
8.01
7.61
6.01
4.01
2.00
30.36
26.02
21.69
18.22
17.35
16.48
13.01
8.67
4.34
Scenario Baseline
USD
5
10
15
0
10
20
30
40
Market size (million USD)

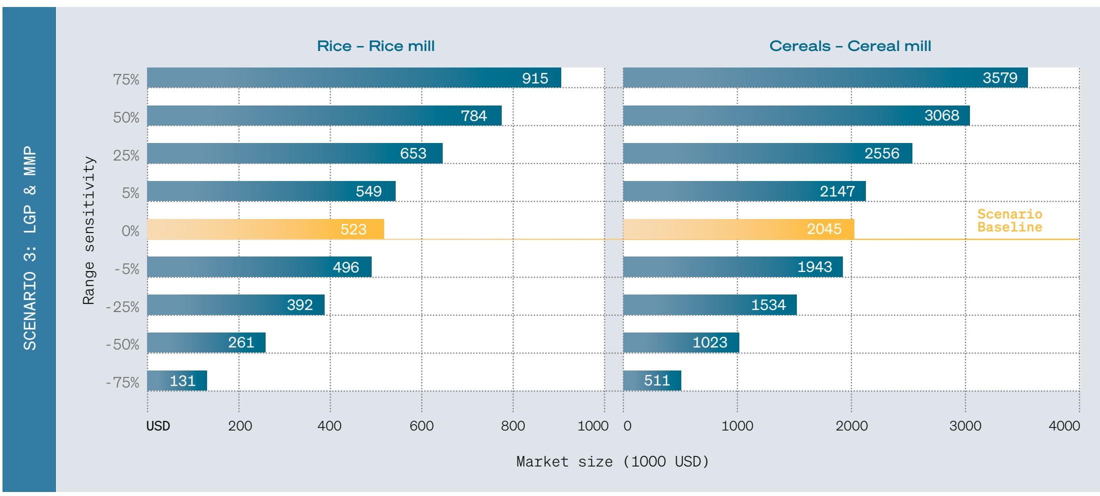

SCENARIO 5: LGP & HMP
Range sensitivity
Rice – Solar husker + polisher
Cereals – Solar mill (small scale)
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
16.66
14.28
11.90
9.99
9.52
9.04
7.14
4.76
2.38
36.07
30.92
25.77
21.64
20.61
19.58
15.46
10.31
5.15
Scenario Baseline
USD
5
10
15
20
0
10
20
30
40
Market size (million USD)

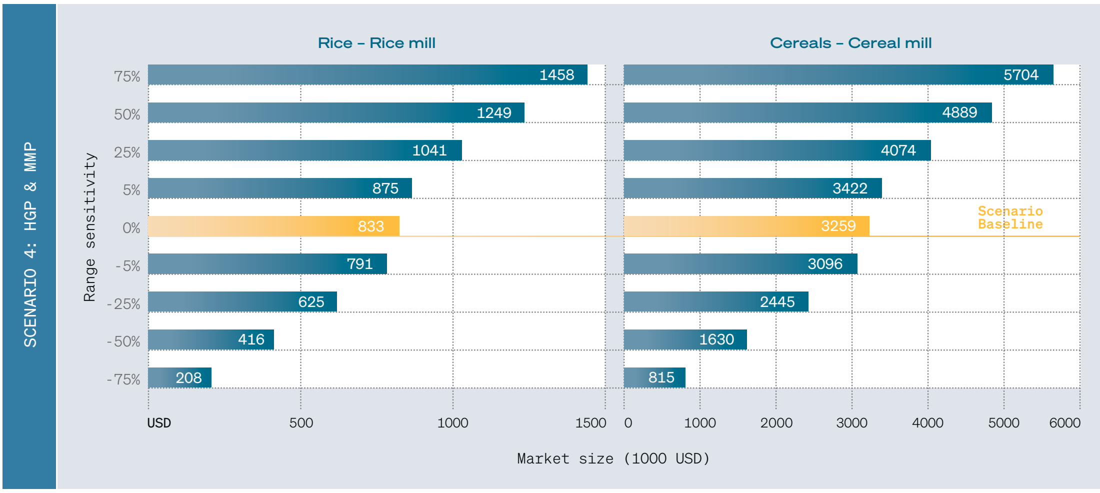

SCENARIO 6: HGP & HMP
Range sensitivity
Rice – Solar husker + polisher
Cereals – Solar mill (small scale)
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
21.03
18.02
15.02
12.62
12.02
11.41
9.01
6.01
3.00
45.54
39.04
32.53
27.33
26.02
24.72
19.52
13.01
6.51
Scenario Baseline
USD
5
10
15
20
25
0
10
20
30
40
50
Market size (million USD)

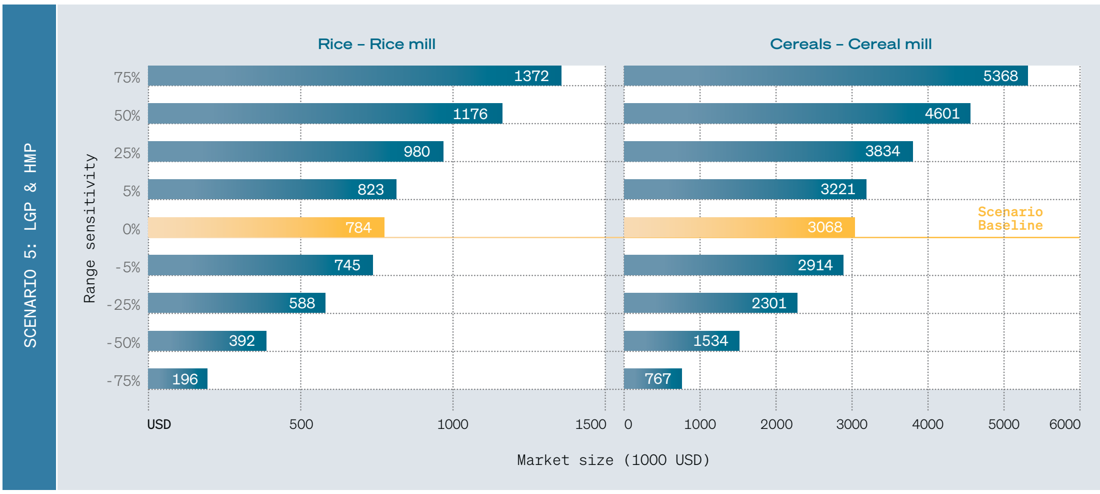
Results type 2

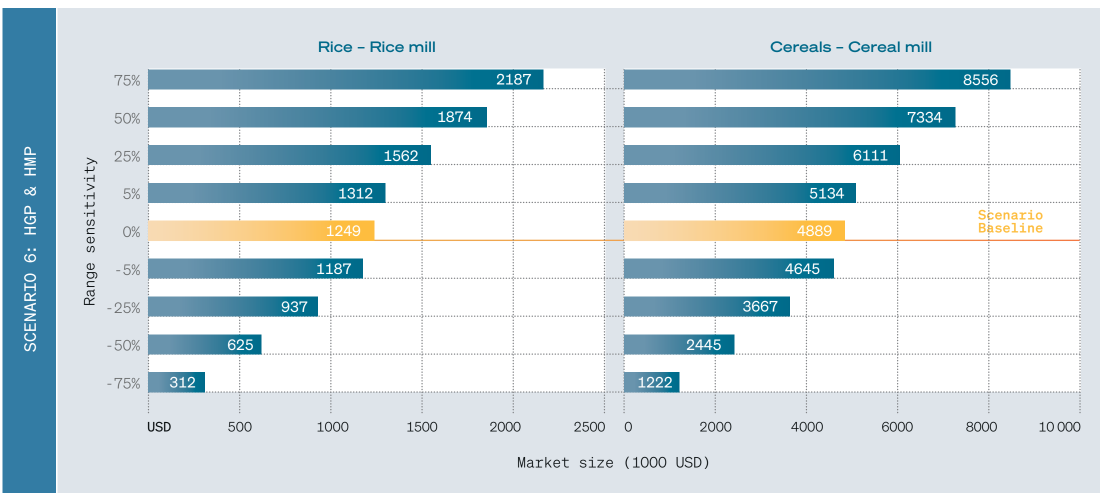






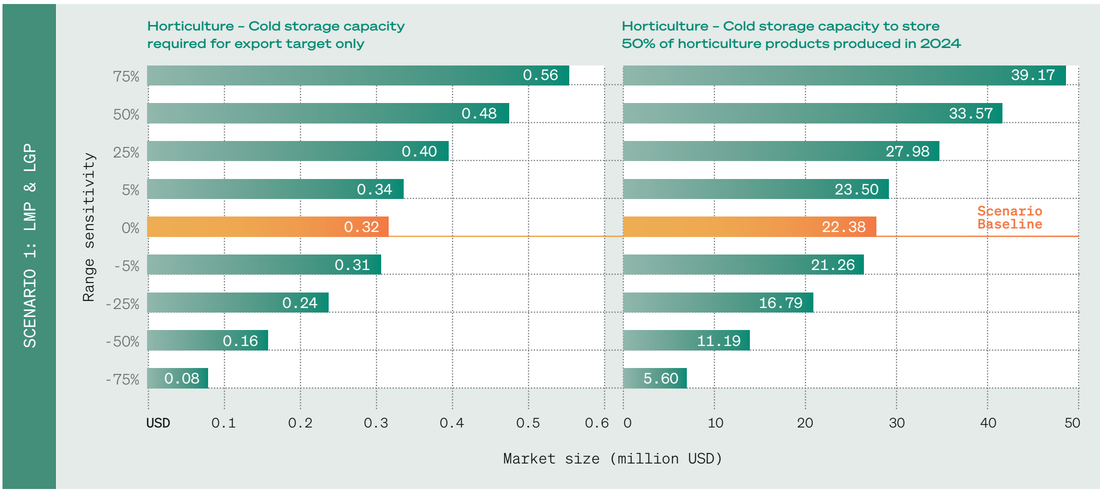

SCENARIO 4: HGP & MMP
Rice – Rice mill
Cereals – Cereal mill
Range sensitivity
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
1458
1249
1041
875
833
791
625
416
208
5704
4889
4074
3422
3259
3096
2445
1630
815
Scenario Baseline
USD
500
1000
1500
0
1000
2000
3000
4000
5000
6000
Market size (1000 USD)

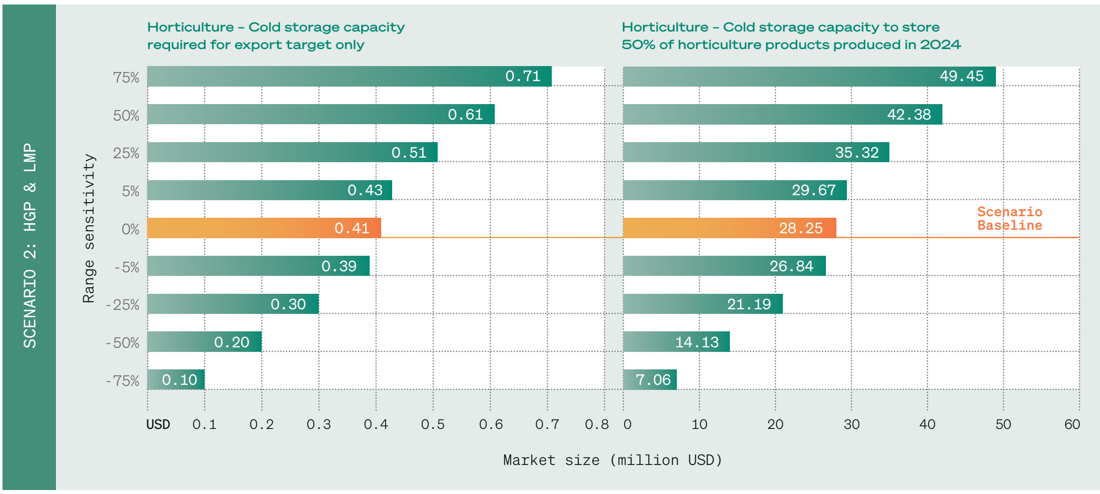

SCENARIO 5: LGP & HMP
Rice – Rice mill
Cereals – Cereal mill
Range sensitivity
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
1372
1176
980
823
784
745
588
392
196
5368
4601
3834
3221
3068
2914
2301
1534
767
Scenario Baseline
USD
500
1000
1500
0
1000
2000
3000
4000
5000
6000
Market size (1000 USD)

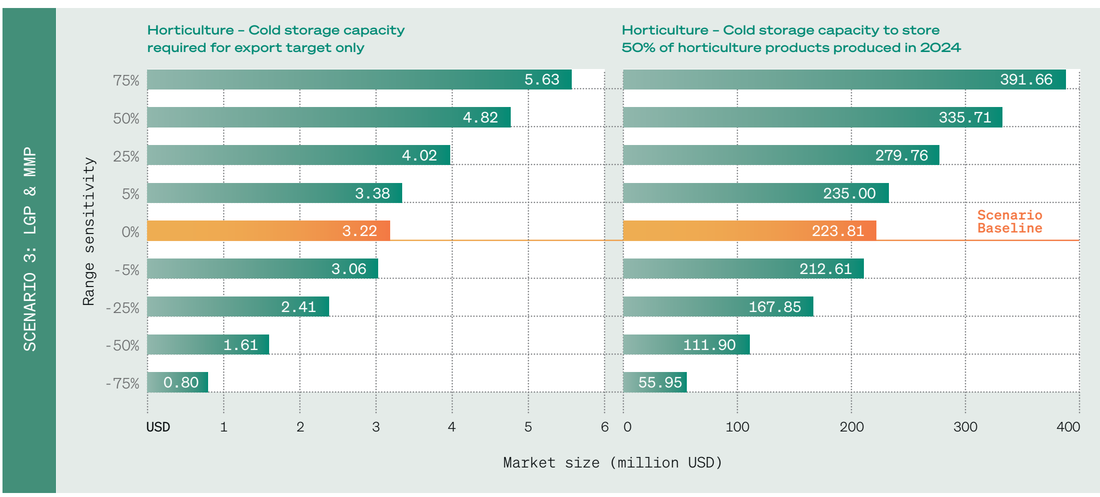

SCENARIO 6: HGP & HMP
Rice – Rice mill
Cereals – Cereal mill
Range sensitivity
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
2187
1874
1562
1312
1249
1187
937
625
312
8556
7334
6111
5134
4889
4645
3667
2445
1222
Scenario Baseline
USD
500
1000
1500
2000
2500
0
2000
4000
6000
8000
10 000
Market size (1000 USD)

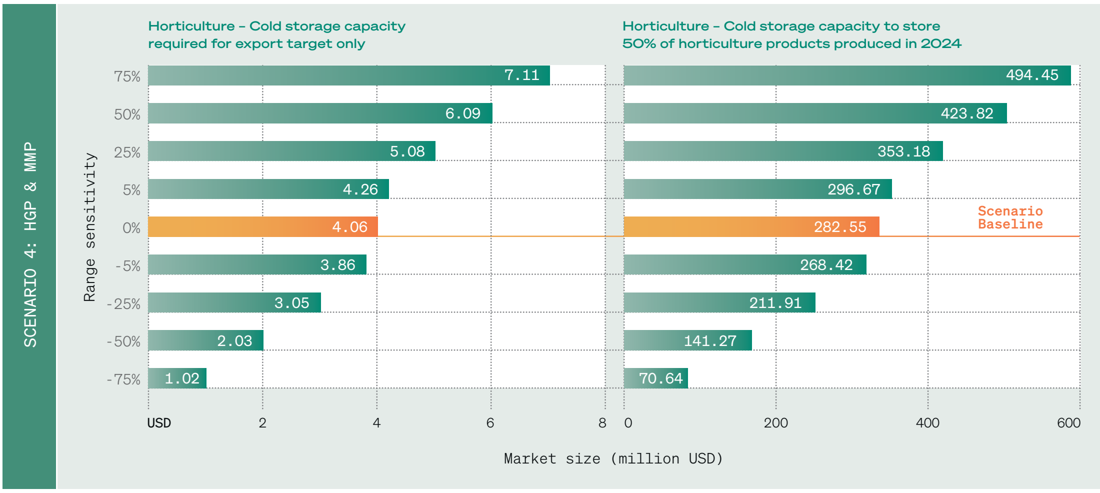
HORTICULTURE VALUE CHAIN (FRUITS, VEGETABLES, ROOTS AND TUBERS, BEANS)

Results type 1

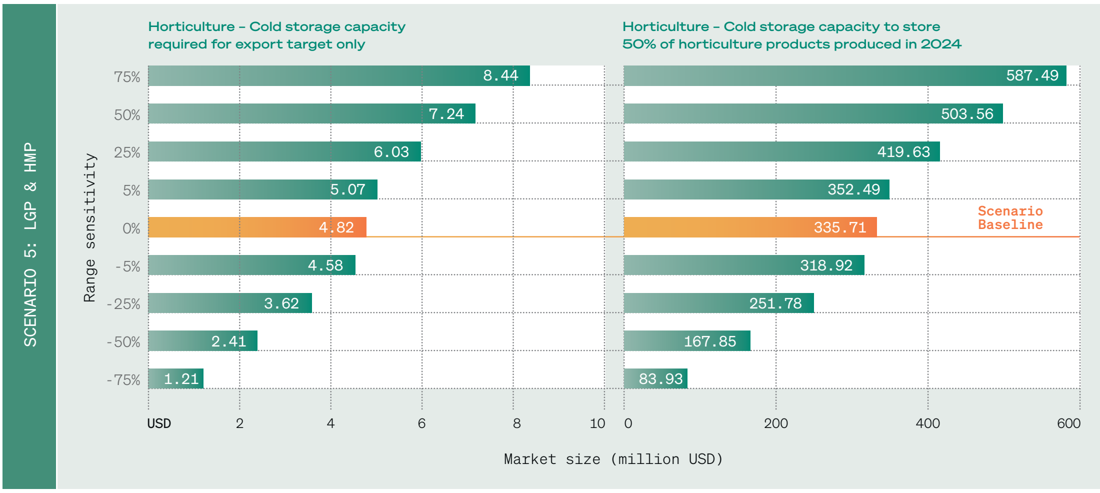




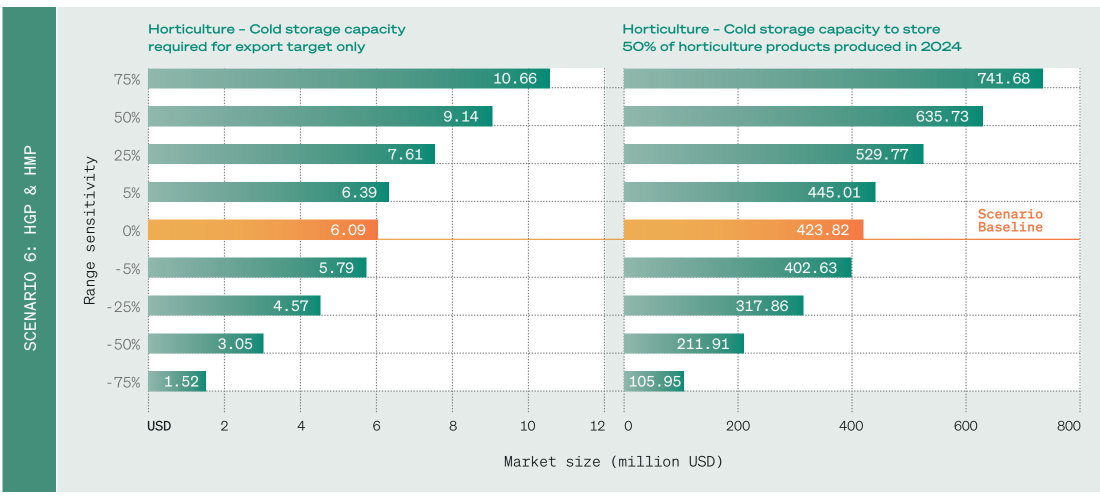




SCENARIO 4: HGP & MMP
Horticulture – Cold storage capacity required for export target only
Horticulture – Cold storage capacity to store 50% of horticulture products produced in 2024
Range sensitivity
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
7.11
6.09
5.08
4.26
4.06
3.86
3.05
2.03
1.02
494.45
423.82
353.18
296.67
282.55
268.42
211.91
141.27
70.64
Scenario Baseline
USD
2
4
6
8
0
200
400
600
Market size (million USD)

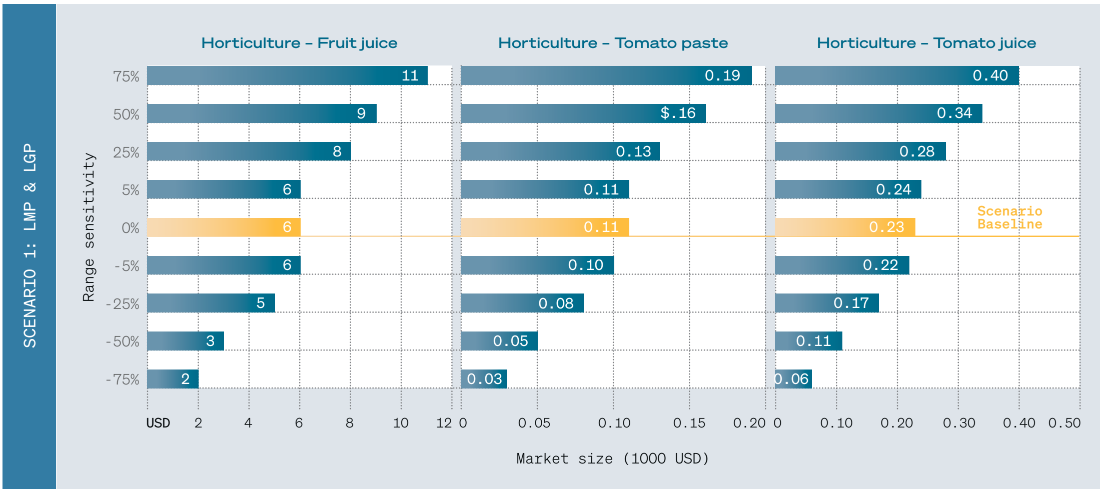


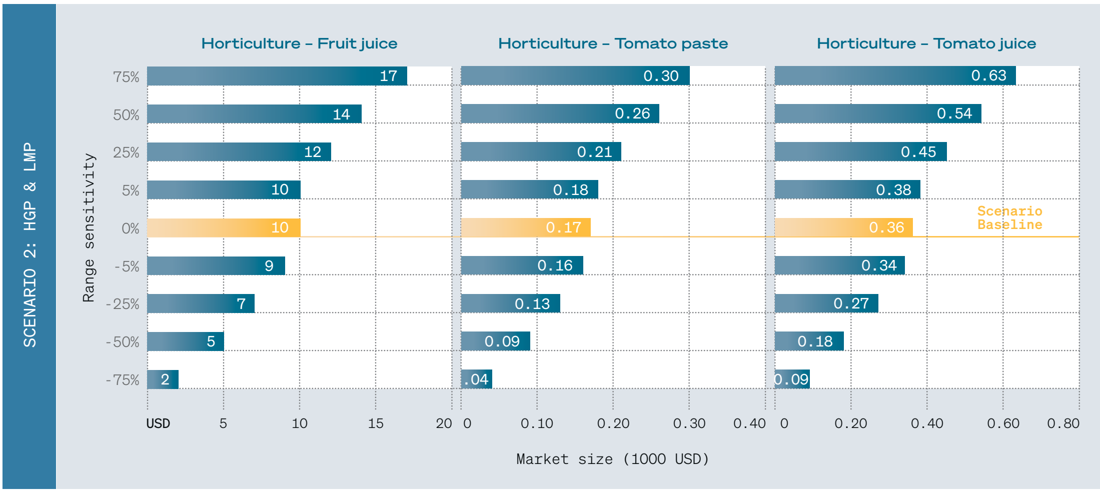
SCENARIO 5: LGP & HMP
Horticulture – Cold storage capacity required for export target only
Horticulture – Cold storage capacity to store 50% of horticulture products produced in 2024
Range sensitivity
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
8.44
7.24
6.03
5.07
4.82
4.58
3.62
2.41
1.21
587.49
503.56
419.63
352.49
335.71
318.92
251.78
167.85
83.93
Scenario Baseline
USD
2
4
6
8
10
0
200
400
600
Market size (million USD)

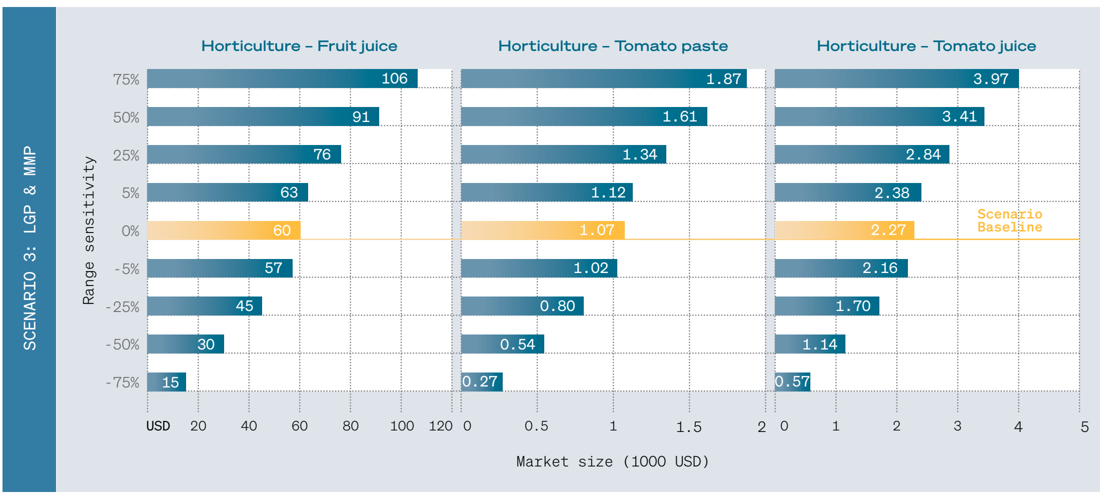


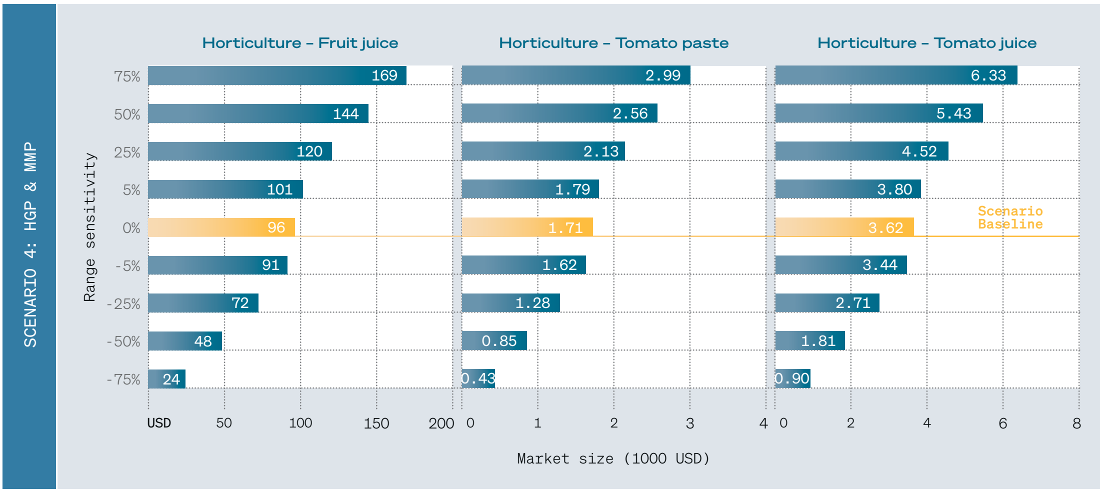
SCENARIO 6: HGP & HMP
Horticulture – Cold storage capacity required for export target only
Horticulture – Cold storage capacity to store 50% of horticulture products produced in 2024
Range sensitivity
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
10.66
9.14
7.61
6.39
6.09
5.79
4.57
3.05
1.52
741.68
635.73
529.77
445.01
423.82
402.63
317.86
211.91
105.95
Scenario Baseline
USD
2
4
6
8
10
12
0
200
400
600
800
Market size (million USD)

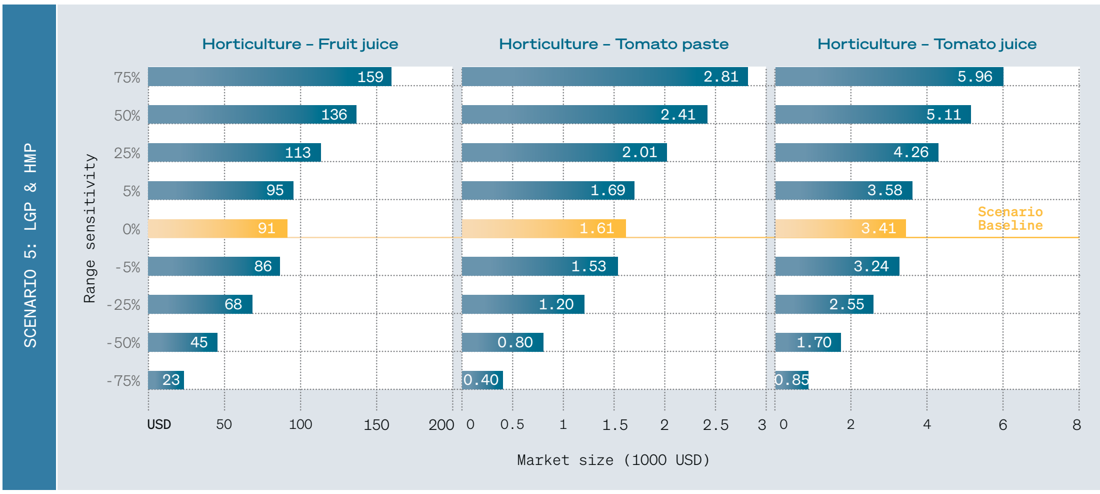
Results type 2

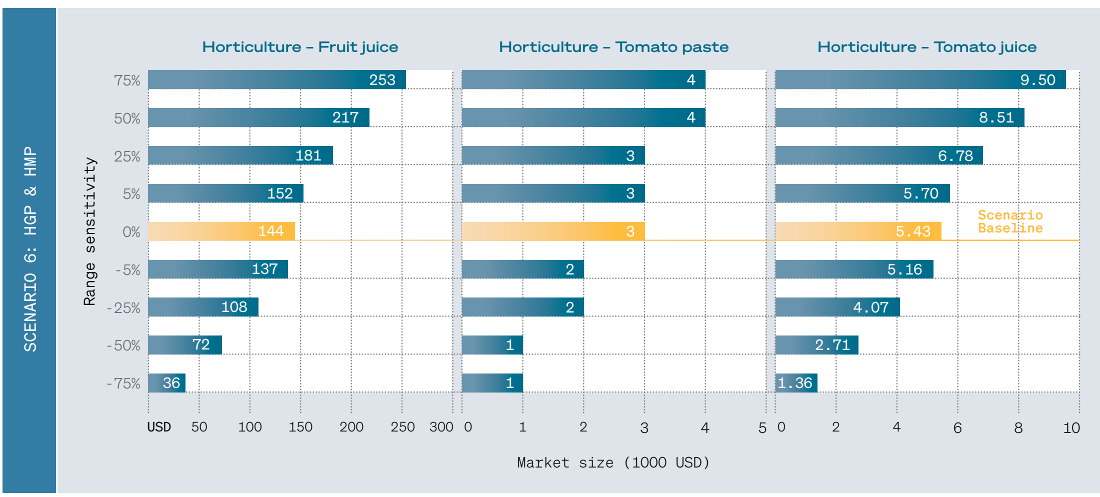




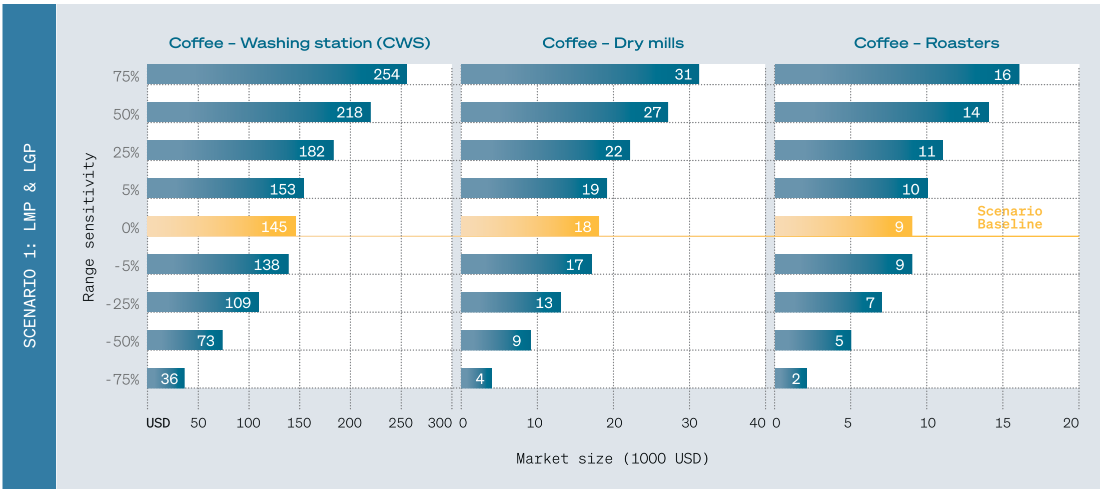


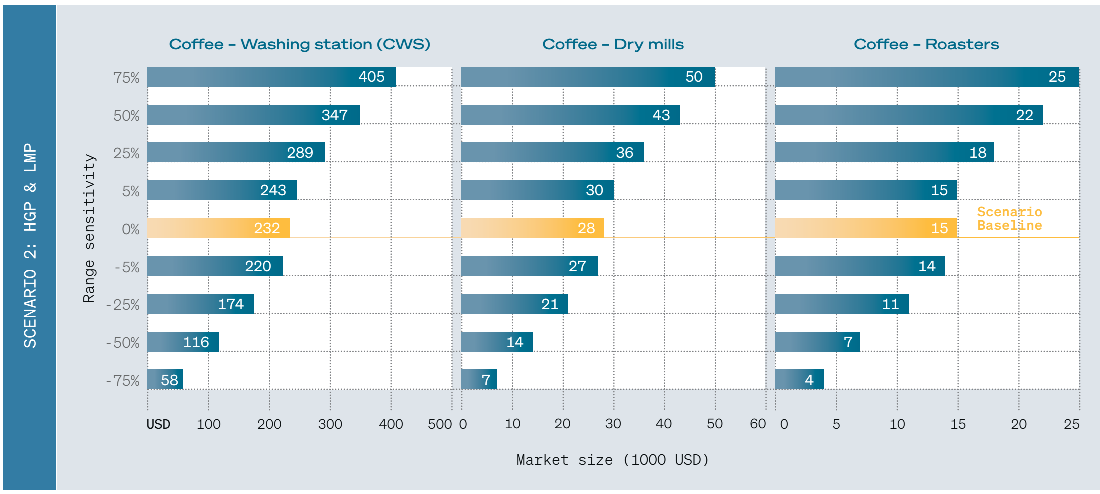

SCENARIO 4: HGP & MMP
Horticulture – Fruit juice
Horticulture – Tomato paste
Horticulture – Tomato juice
Range sensitivity
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
169
144
120
101
96
91
72
48
24
2.99
2.56
2.13
1.79
1.71
1.62
1.28
0.85
0.43
6.33
5.43
4.52
3.80
3.62
3.44
2.71
1.81
0.90
Scenario Baseline
USD 50 100 150 200
0 1 2 3 4
0 2 4 6 8
Market size (1000 USD)

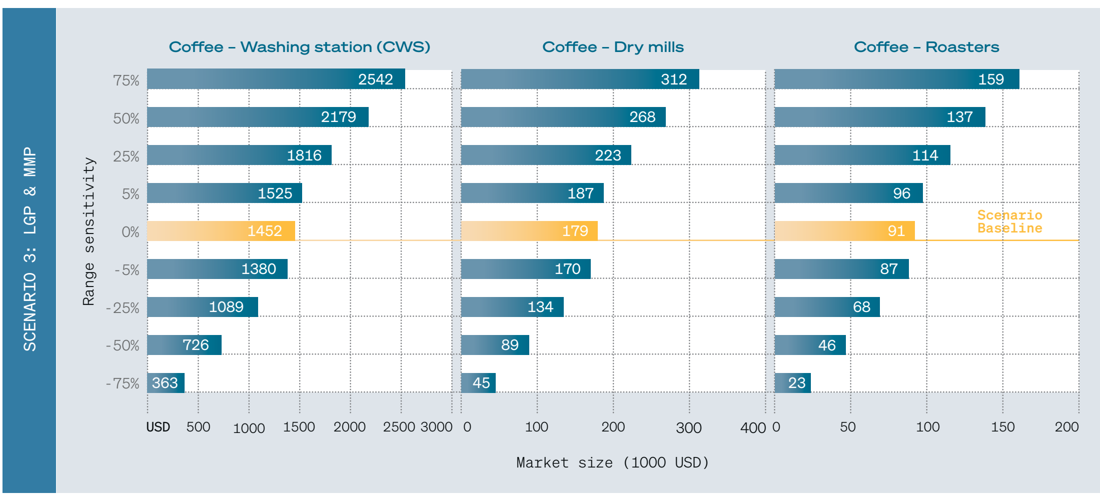

SCENARIO 5: LGP & HMP
Horticulture – Fruit juice
Horticulture – Tomato paste
Horticulture – Tomato juice
Range sensitivity
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
159
136
113
95
91
86
68
45
23
2.81
2.41
2.01
1.69
1.61
1.53
1.20
0.80
0.40
5.96
5.11
4.26
3.58
3.41
3.24
2.55
1.70
0.85
Scenario Baseline
USD 50 100 150 200
0 0.5 1 1.5 2 2.5 3
0 2 4 6 8
Market size (1000 USD)

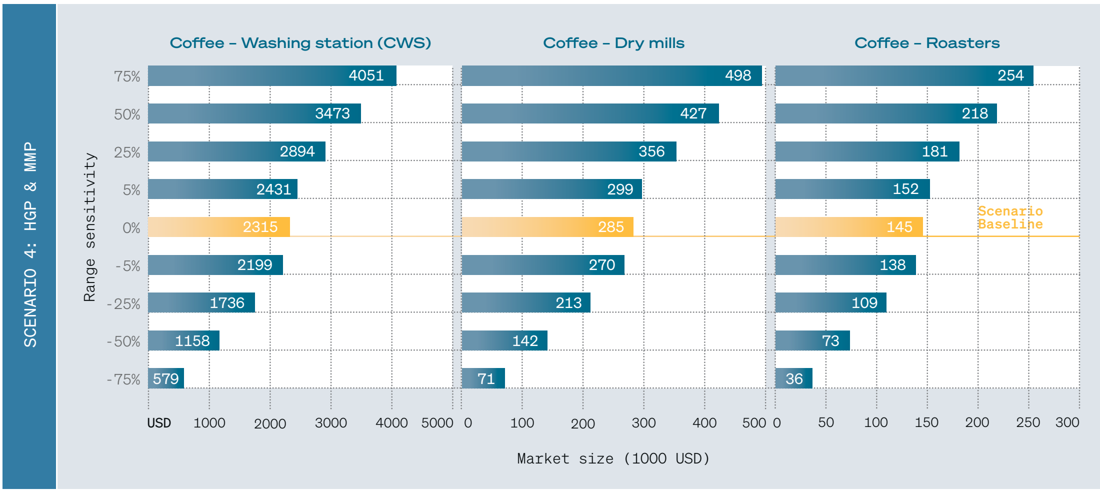

SCENARIO 6: HGP & HMP
Horticulture – Fruit juice
Horticulture – Tomato paste
Horticulture – Tomato juice
Range sensitivity
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
253
217
181
152
144
137
108
72
36
4
4
3
3
3
2
2
1
1
9.50
8.51
6.78
5.70
5.43
5.16
4.07
2.71
1.36
Scenario Baseline
USD 50 100 150 200 250 300
0 1 2 3 4 5
0 2 4 6 8 10
Market size (1000 USD)

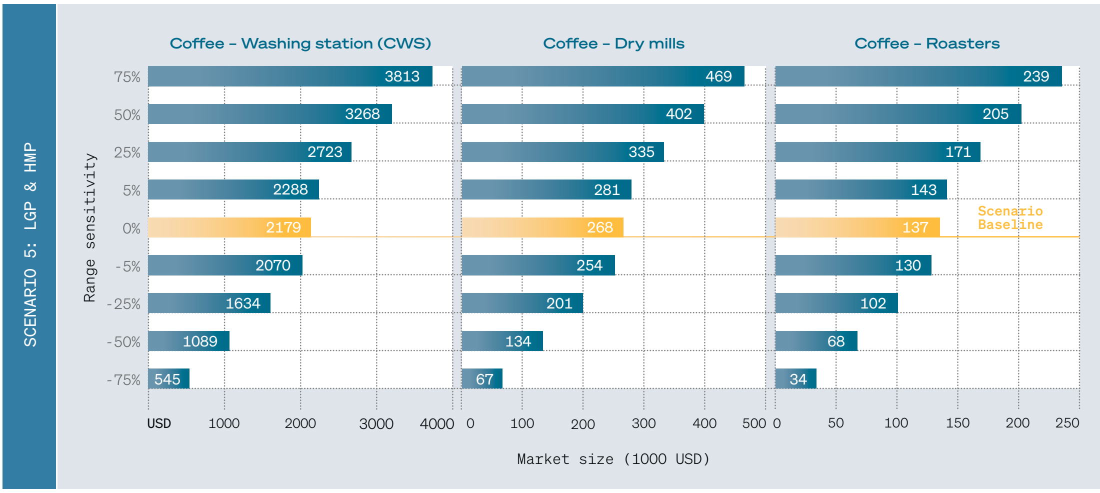
Results type 2

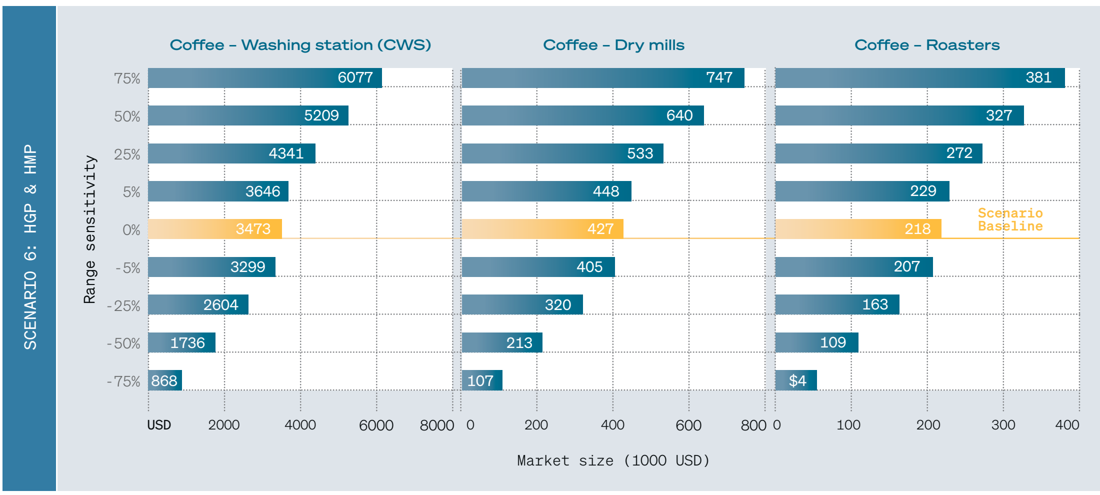




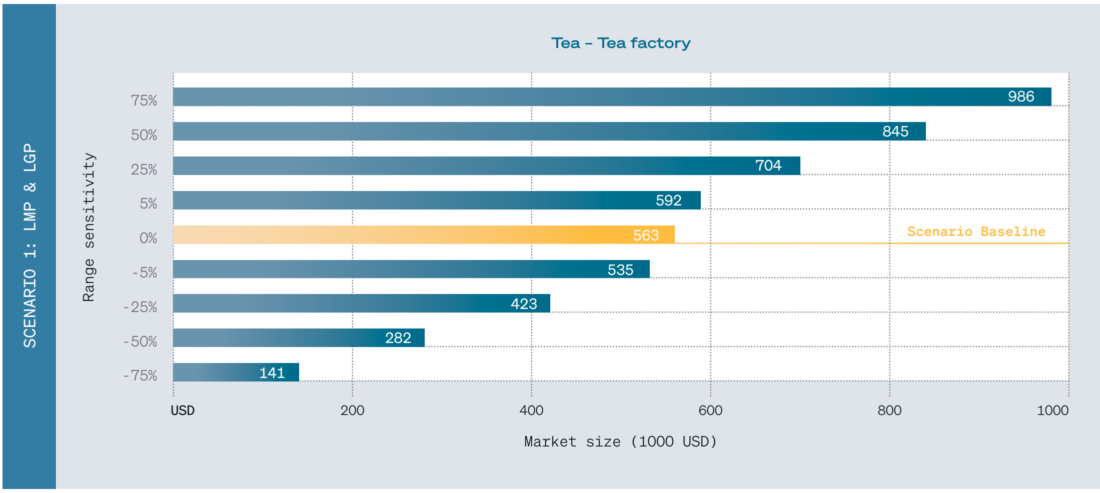


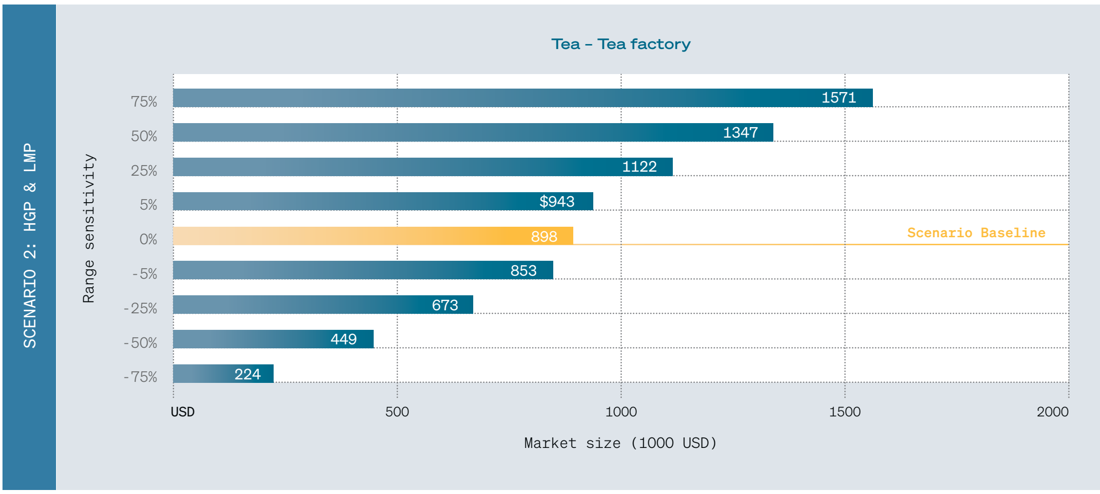

SCENARIO 4: HGP & MMP
Range sensitivity
Coffee – Washing station (CWS)
Coffee – Dry mills
Coffee – Roasters
75% 50% 25% 5% 0% -5% -25% -50% -75%
4051 3473 2894 2431 2315 2199 1736 1158 579
498 427 356 299 285 270 213 142 71
254 218 181 152 145 138 109 73 36
Scenario Baseline
USD 1000 2000 3000 4000 5000
0 100 200 300 400 500
0 50 100 150 200 250 300
Market size (1000 USD)

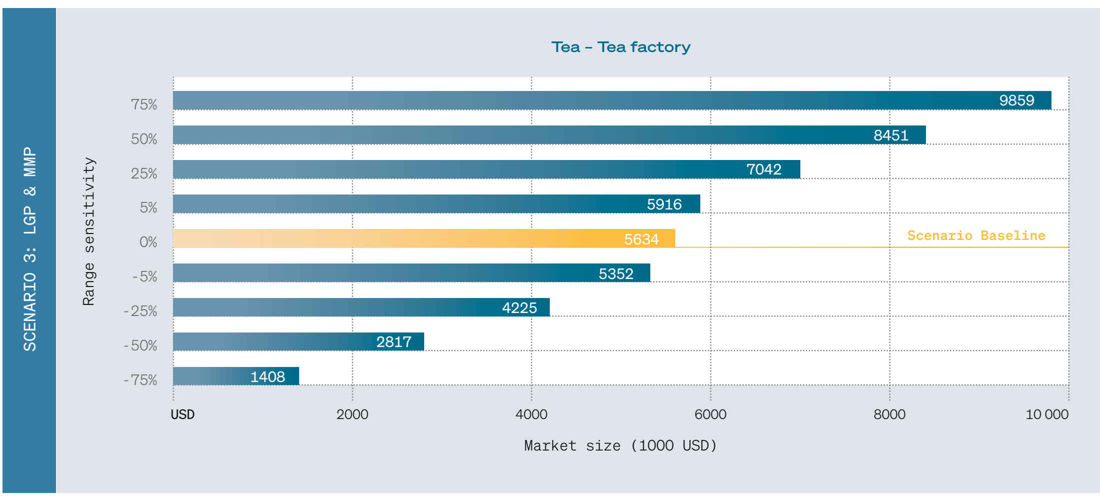

SCENARIO 5: LGP & HMP
Range sensitivity
Coffee – Washing station (CWS)
Coffee – Dry mills
Coffee – Roasters
75% 50% 25% 5% 0% -5% -25% -50% -75%
3813 3268 2723 2288 2179 2070 1634 1089 545
469 402 335 281 268 254 201 134 67
239 205 171 143 137 130 102 68 34
Scenario Baseline
USD 1000 2000 3000 4000
0 100 200 300 400 500
0 50 100 150 200 250
Market size (1000 USD)

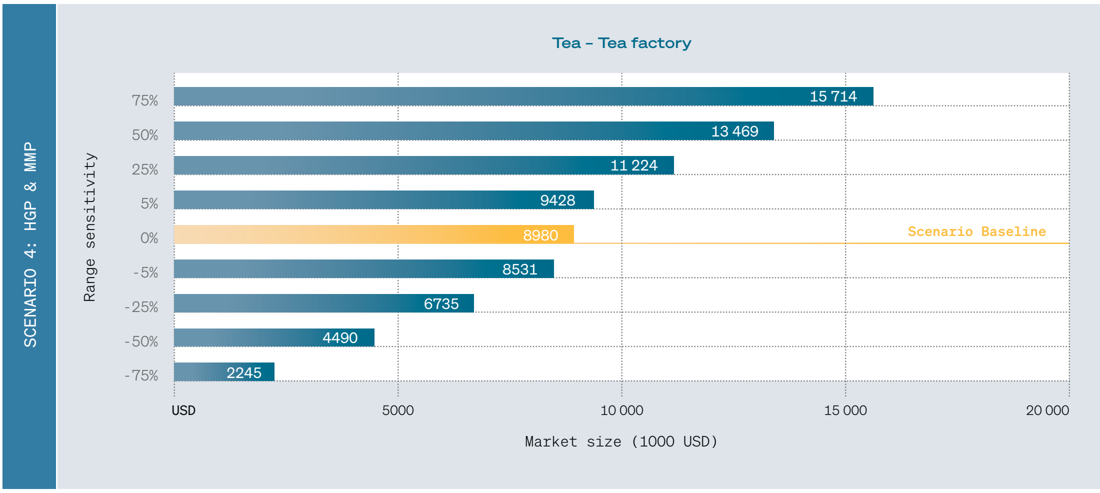

SCENARIO 6: HGP & HMP
Range sensitivity
Coffee – Washing station (CWS)
Coffee – Dry mills
Coffee – Roasters
75% 50% 25% 5% 0% -5% -25% -50% -75%
6077 5209 4341 3646 3473 3299 2604 1736 868
747 640 533 448 427 405 320 213 107
381 327 272 229 218 207 163 109 $4
Scenario Baseline
USD 2000 4000 6000 8000
0 200 400 600 800
0 100 200 300 400
Market size (1000 USD)

Results type 2

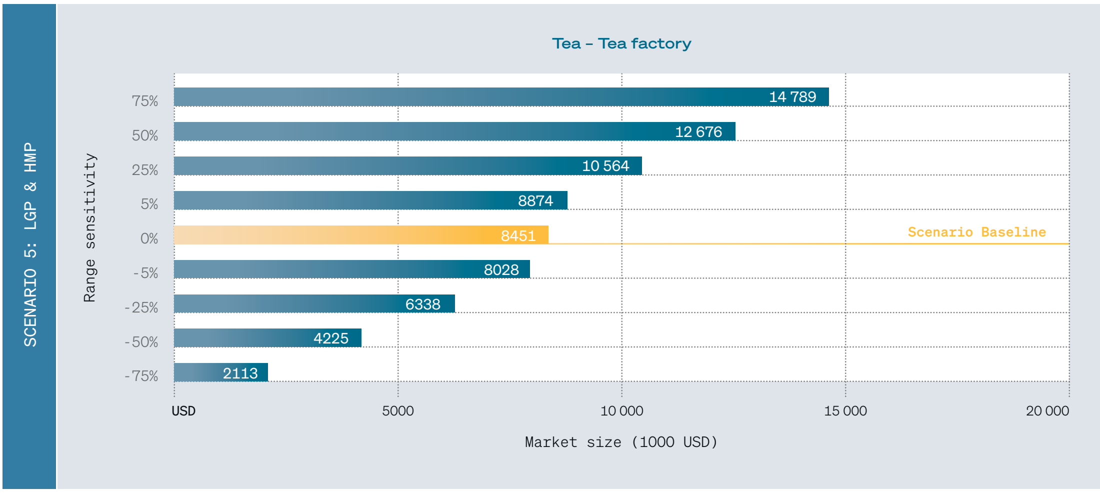




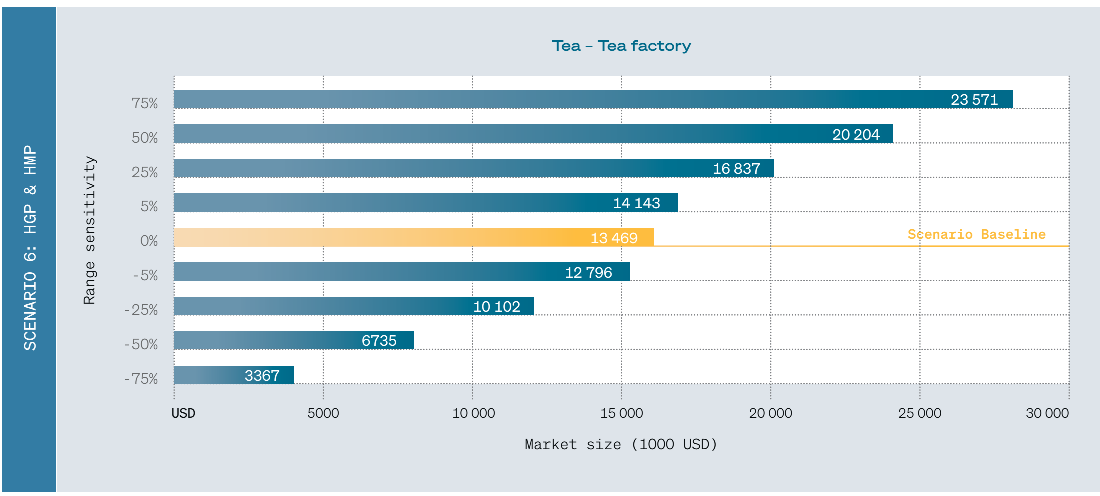




SCENARIO 4: HGP & MMP
Tea – Tea factory
Range sensitivity
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
15 714
13 469
11 224
9428
8980
8531
6735
4490
2245
Scenario Baseline
USD
5000
10 000
15 000
20 000
Market size (1000 USD)



SCENARIO 5: LGP & HMP
Tea – Tea factory
Range sensitivity
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
14 789
12 676
10 564
8874
8451
8028
6338
4225
2113
Scenario Baseline
USD
5000
10 000
15 000
20 000
Market size (1000 USD)



SCENARIO 6: HGP & HMP
Tea – Tea factory
Range sensitivity
75%
50%
25%
5%
0%
-5%
-25%
-50%
-75%
23 571
20 204
16 837
14 143
13 469
12 796
10 102
6735
3367
Scenario Baseline
USD
5000
10 000
15 000
20 000
25 000
30 000
Market size (1000 USD)

Sustainable and efficient agri-food systems depend on stable access to energy, from farm to plate. But for many developing countries across the world, limited access to energy hinders the growth of modern agri-food systems, prevents farmers from producing higher value products and results in food losses. For Rwanda, which is committed to achieving energy access for all by 2024, the adoption of solar technologies has become a national priority and could offer an opportunity for the country's agriculture sector to transition to less fossil fuel-intensive production systems. Using a methodological approach, this report provides a broad estimate of existing opportunities for the uptake of solar energy technologies within Rwanda's agri-food sector. The assessment identifies the country's agri-food chains, breaking them down into their main production and processing blocks and assessing energy requirements required at each stage. Results, presented by different agri-food value chain groups, include a baseline analysis and sensitivity analysis to market penetration and growth in production. The methodology can be applied to other options available within the broad range of renewable energy technologies.

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