Techno-Economic Assessment on the Feasibility of Solar Photovoltaic Systems for Tea Production in Kenya

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Sammanfattning

Teindustrin i Kenya är en av landets viktigaste, med stor påverkan på både ekonomin och den socioekonomiska utvecklingen. Samtidigt är teproduktion en mycket energiintensiv industri som påverkas mycket av elpris och höga produktionskostnader. Tack vare gynnsamma värderförhållanden och växande ambition för förnybar energi i Kenya utgör solcellssystem (Solar Photovoltaic, PV-system) en potentiell möjlighet för en mer kostnadseffektiv teproduktion i landet.

Denna studie syftar till att undersöka den tekno-ekonomiska genomförbarheten för solcessystem inom teproduktion i Kenya. Studien genomfördes tillsammans med Miale Solar, en leverantör av solcellssystem, och kombinerar kvalitativa fältbaserade insikter med en Tekno-Ekonomisk Analys (TEA). Analysen inkluderade både ett leverantörsperspektiv genom Miale Solar, och ett kundperspektiv med fokus på medelstora tefabriker under ledning av Kenya Tea Development Agency (KTDA). Flera nätanslutna PV-system med och utan Battery Energy Storage Systems (BESS) analyserades och utvärderades utifrån teknisk och ekonomisk försvarbarhet. Studien baserades på både kvalitativ och kvantitativ data från intervjuer, observationer, simuleringar och finansiella beräkningar. Den tekniska analysen utvärderar tillgången till solenergi och dess relation till tefabrikernas elkonsumption, medan den finansiella analysen bygger på Levelized Cost of Energy (LCOE), Genomsnittligt Elpris (AEP), Nettonuvärde (NPV), Internränta (IRR), Återbetalningstid (PP) och Vinstmarginal (PM).

Resultaten från studien visar att PV-system har stor teknisk potential inom te-industrin i Kenya, men att solenergi utan batterilagring inte fullt ut kan täcka tillverkningsprocessens elbehov, eftersom en stor del av elanvändningen sker utanför dygnets soltimmar. Vidare visade sig BESS vara nödvändigt för att säkerställa förbättring av energisäkerheten. Den finansiella analysen visar att nätanslutna PV-system bidrog till minskade elkostnader, men att möjligheten att skapa värde från överskottsel är avgörande för hur stor nyttan blir. Nuvarande regelverk försvårar användningen av överskottsel genom Net Metering, och även om BESS bidrar till bättre nyttjandegrad av solcellssystemen och förbättrad energisäkerhet visade sig system utan energilagring generellt vara mer finansiellt försvarbara på grund av lägre investeringskostnader.

Sammanfattningsvis visar studien att PV-system kan bidra till en mer kostnadseffektiv teindustri i Kenya, men att genomförbarheten fortsatt är beroende av systemdesign, finansieringsstrukturer och regelverk.

Nyckelord: Solenergi, Solceller (PV), Förnybar energi, Hållbara energisystem, Tekno-Ekonomisk Analys (TEA), Energisystemanalys (ESA), Teproduktion, Teindustrin, Industriella energisystem och Kenya.

Abstract

The tea sector is one of Kenya's most important industries, with a big impact on the country's economy and socio-economic development. At the same time, tea manufacturing is highly energy-intensive and strongly affected by electricity tariffs and high production costs. Due to the favorable weather conditions and growing renewable energy ambitions in Kenya, Solar Photovoltaic (PV) systems present a potential opportunity for a more cost-efficient tea production process.

The aim of this study was to assess the techno-economic feasibility of solar PV for tea manufacturing in Kenya. The study was conducted in collaboration with PV system supplier Miale Solar and combines qualitative field-based insights from stakeholders in the Kenyan tea- and energy sectors with a Techno-Economic Analysis (TEA). The analysis included both the supplier perspective through Miale Solar, and a customer perspective focused on medium-sized tea factories managed by Kenya Tea Development Agency (KTDA). Several grid-tied PV systems with and without Battery Energy Storage Systems (BESS) were assessed and evaluated. The study is based on a mixed-methods approach including interviews, observations, simulations and financial calculations. The technical assessment evaluate solar resource availability and its alignment with the tea factory load profile while the financial analysis includes Levelized Cost of Energy (LCOE), Average Electricity Price (AEP), Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PP), and Profit Margin (PM).

The results from the study indicate that solar PV systems have strong technical potential within the Kenyan tea sector, but that solar energy systems without storage cannot fully support the manufacturing process since large parts of electricity consumption occurs outside of daylight hours. Moreover, BESS was found necessary to ensure improvements in reliability and energy security. The financial analysis shows that grid-tied PV systems contributed to reduced electricity costs, but to which degree is highly dependent on whether surplus electricity can create value or not. Current regulatory conditions make utilization of excess energy through Net Metering difficult, and while BESS contributes to higher utilization and improved energy security, systems without storage solutions were generally found to be more financially viable due to lower investment cost.

Overall, the study concludes that solar PV systems can contribute to a more cost-efficient tea industry in Kenya, but that feasibility remains dependent on system design, financing structures, and regulatory conditions.

Keywords: Solar energy, Solar Photovoltaic (PV), Renewable energy, Sustainable energy systems, Techno-Economic Analysis (TEA), Energy Systems Analysis (ESA), Tea manufacturing, Tea industry, Industrial energy systems and Kenya

Use of AI

During this study, AI tools have been used in a limited and controlled manner. These tools have primarily been used to improve the structure, grammar and phrasing throughout the report. In addition, AI tools have been used for practical purposes; to clean interview transcript, develop and improve the MATLAB codes used for the financial calculations, and to create a figure that highlights specific areas on a map. Lastly, it has been used as a support for finding relevant literature and sources. The authors have checked and reviewed these sources to ensure that all information used in this study is accurate and reliable. AI has not been used during the data analysis or evaluation process. All analytical decisions, interpretations and conclusions presented in this report were made independently by the authors.

Acknowledgments

This thesis has been conducted through a collaboration with the Department of Energy Sciences at Lund University, at the Faculty of Engineering (LTH), and Miale Solar Inventions in Kenya. We would like to express our sincere gratitude to the people and organisations who made this study possible.

Firstly, we want to thank our supervisor Martin Andersson, at LTH, for his guidance, support and valuable feedback throughout the course of this thesis. We have appreciated your advice and encouragement, both during the planning phase, the two months we spent in Kenya and during the analysis and writing period throughout the rest of our time in Lund.

Secondly, we want to thank our case company, Miale Solar, both for giving us a warm welcoming to Nairobi and Kenya, but also for their generous collaboration. Miale has contributed with many valuable insights for our project, and has guided us to relevant stakeholders within the Kenyan tea sector.

We would also like to sincerely thank the Kenya Tea Development Agency (KTDA) for their openness and willingness to share data and their experiences with us. We are especially grateful for the site visits at tea factories that KTDA helped us arrange. Both the visits and the meetings helped us gain a better understanding of their tea industry and the current energy situation. Overall, we wish to thank everyone who took the time to participate in interviews for this study. Your insights have been very valuable and helpful for the development of this thesis.

Finally, a special thank you to Vilma Delden, with whom we have been collaborating and working closely during this time. Your findings have made an important contribution to our work and you have been an important thought partner for our method and project structure. The field studies in Kenya would not have been the same without you.

Ellen Langlet and Ebba Holmberg
Lund, May 2026

Preface

This Master Thesis was conducted by Ellen Langlet and Ebba Holmberg during the spring semester of 2026, as the final part of the Master of Science program in Mechanical Engineering at LTH. Both authors have contributed equally to the thesis and have collaborated throughout the whole process, from the initial idea to the final report. Parts of the project tasks, especially the pure report writing, have been divided between the authors, where Holmberg focused on empirics and analysis, as well as the theoretical background. Langlet mainly focused on the introduction, theoretical framework and methodology, discussion and evaluation. For the quantitative process, Holmberg accounted for the simulations while Langlet took more responsibility over MATLAB calculations. However, both authors collaborated, discussed, and cross-read the writing of the whole report, and all chapter include subsections by both authors. Especially for the analysis and discussion, both authors worked together to identify the key findings from the results and interpret those in relation to the Techno-Economic Assessment framework and the chosen research questions.

The authors have also collaborated with Vilma Delden throughout the course of this thesis. All collected data, interviews and email correspondence were conducted together with Delden. In addition, the techno-economic analysis in this study has been based on simulated and optimized results from Delden. This collaboration has aimed to conduct a comprehensive analysis of how Solar Photovoltaic systems can be used in the tea industry by combining a detailed technical perspective with a techno-economic assessment.

Contents

Nomenclature

AC	Alternating Current
AEP	Average Electricity Price
BESS	Battery Energy Storage System
C&I	Commercial and Industrial
CapEx	Capital Expenditure
CTC	Cutting, Tearing and Curling
DNI	Direct Normal Irradiance
ESA	Energy Systems Analysis
IRR	Internal Rate of Return
KES	Kenyan Shilling
kg	Kilogram
KPLC	Kenya Power & Lighting Plc
KTDA	Kenya Tea Development Agency
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelized Cost of Energy
MW	Megawatt
NPV	Net Present Value
O&M	Operations and Maintenance
OpEx	Operational Expenditure
PP	Payback Period
PPA	Power Purchase Agreement
PV	Photovoltaic
SAM	System Advisor Model
TBK	Tea Board of Kenya
TEA	Techno-Economic Analysis
USD	United States Dollar

Note: Currency conversions have been made from Kenyan Shilling (KES) to United States Dollar (USD). The current value during the writing of the report was, according to the Central Bank of Kenya (22/04/2026): 1 KES = 0.0077 USD.

1 Introduction

This chapter introduces the research context and the case company for the field study period in Kenya. It outlines the problem addressed in this study, presents the aim and research questions, as well as the scope and limitations of the work. Lastly, the structure of the thesis is described to provide an overview of how each chapter contributes to answering the research question.

1.1. Contextual background

Tea is Kenya's largest export, and the whole industry plays a vital role in the country's national economy. Black tea accounts for over 20% of foreign exchange earnings, corresponding to over 1.3 billion USD annually [1]. This ranks Kenya as a global leader within the industry, with over 500 million kilogram (kg) tea produced annually, and the sector contributes significantly to it's socio-economic state and development. The tea industry ecosystem provides work and support to about 5 million people, from farmers and factory workers to brokers and exporters, making it one of the leading sources of livelihood in the country [2].

Despite the tea sector's importance, it is also one of the country's most energy-intensive value chains [3]. Particularly the manufacturing process in tea factories requires both electrical and thermal energy across multiple processing stages, including withering, fermentation, and drying. Energy use in tea production is dominated by thermal energy, primarily supplied through biomass such as firewood. While electrical energy constitutes a smaller share, approximately 9–15%, it accounts for nearly 60% of energy costs due to the high tariffs [4], [5]. Moreover, since the industry as a whole is so energy intensive, even a small share of the total consumption accounts for a large number. The energy needed to produce one kg of tea is approximately 3-6 kilowatt hours (kWh) thermal (mainly supplied from wood combustion), and 0.2-0.5 kWh of electrical energy [6]. In tea production, energy is generally the second largest cost driver after raw materials [3], on average 30% of the total production cost [7].

Beyond the cost, the high energy consumption makes the tea industry a heavy contributor to environmental challenges, such as deforestation and greenhouse gas emissions. However, there are several both global and regional initiatives supporting the development of Kenya as a climate resilient economy, pursuing universal and 100% renewable energy access by 2030. Kenya's Commercial and Industrial (C&I) sector possesses significant potential and a strong willingness to transitioning to renewable energy [8]. Due to the country's geographical position at the equator and its abundant insolation levels, the country has great potential to utilize particularly solar energy. Kenya's total solar generation potential is approximately 15 gigawatt (GW), making it one of the global leading countries in this area [9].

These factors combined creates both reason and opportunity to transition energy-intensive industries, such as tea manufacturing, toward more sustainable and cost-efficient energy systems [8].

1.2. Miale Solar Inventions

Miale Solar plays an important role in deploying Solar Photovoltaic (PV) systems for Commercial and Industrial (C&I) clients as well as for residential users across the East Africa region [10]. The firm is Swedish-founded but operates solely in Kenya, and most employees are Kenyan. Their services range from concept, engineering, and system design to procurement, installation, service and maintenance. They offer three different financing models:

- **Outright Purchase:** Miale Solar will design and install a solar system for the client who will make a one-time upfront investment, and thereby take full ownership of the solar system from the moment of installation, including the panels, inverters, and other components, as well as its operation and maintenance [11].
- **Lease-to-Own:** Miale Solar will design and install a solar system for the client, who can lease the solar equipment while progressively gaining full ownership over an agreed period. The client makes no upfront investment but pays a fixed fee to Miale Solar monthly. After a period of time, the client will take over full ownership [12].
- **Power Purchase Agreement (PPA):** Miale Solar will design and install a PV system for the client, and thereafter charge the client based on the energy they consume. The client makes no upfront investment, and the price per kWh is calculated as a discount on the corresponding consumption from what the national electricity grid company, Kenya Power and Lighting Company (KPLC) would charge [13].

Miale Solar has been active since 2016 and, as of the end of Q1 2026, has a portfolio of around 100 ongoing or operational projects with a total installed capacity of 13.8 MW, ranging from 12 kW to 1,230 kW. Their solar PV systems can be both grid-tied or off-grid, with or without a Battery Energy Storage System (BESS) [10]. Miale's solar PV system offers stable, long-term cost efficiency and can contribute to greater energy security for the user, and this show a large potential in addressing several key barriers to sustainable energy adoption in the tea industry.

1.3. Aim and research question

The aim of this study is to assess the feasibility of PV systems in supporting a more cost-efficient and sustainable tea production sector in Kenya. This is achieved through a Techno-Economic Assessment combined with field-based insights from selected industry stakeholders. The thesis specifically seeks to evaluate both the technical feasibility and financial viability of solar PV systems for the tea industry, as well as the practical and strategic role of Miale Solar as a supplier in this transition.

Based on the aim of the thesis, a main research question was formulated to ensure that the thesis fulfills its purpose. Hence, the main research question is:

- *How can solar PV systems contribute to a more cost-efficient tea production in Kenya, from a techno-economic perspective?*

To support the analysis and ensure the main research question is properly addressed, the following sub-questions have been strategically addressed:

- *What technical and operational factors impact the integration of solar PV systems in tea manufacturing?*
- *What is the economic viability and potential profitability of installing solar PV in Kenyan tea factories?*
- *Are there external barriers and incentives that affect the adoption of solar PV solutions in the Kenyan tea sector?*

1.4. Delimitations

This study is subject to several delimitations:

- The study focuses on electrical energy substitution, while thermal energy is not considered for analysis and evaluation (but discussed in relation to system potential).
- The analysis focuses exclusively on monocrystalline PV technology, as this is the technology offered by Miale Solar.
- Weather data used in the analysis is based on long-term averages rather than specific yearly data, assuming relatively stable climatic conditions. Thereby, the future conditions are assumed to remain constant when considered in discussions.
- The case study includes selected tea factories categorized as medium-sized based on finished goods output, and may not fully represent all variations within the Kenyan tea sector.
- This study includes no design optimizations, which would be crucial for fulfilling the main research purpose. Instead, this has been completed by Vilma Delden, who's results have been used as input in this assessment.
- This study does not consider residual value of battery systems after the end-of-life for the PV system, due to the case-specific nature of battery state of health, and added complexity to calculations and system modeling.
- Due to the structure of the System Advisor Model (SAM), the simulations used as input for the financial calculations were limited to first-year outputs for scenarios without BESS, while scenarios with BESS were simulated over the full 25-year assessment period. The financial model therefore accounts for long-term performance by including the full system lifetime, component lifespans, and PV degradation.

These delimitations are used as they narrow down the research focus, and allows for a manageable analysis while still providing relevant insights into the feasibility of solar PV systems within the Kenyan tea sector.

1.5. Thesis outline

This study is divided into several sections and follows the structure shown in Figure 1. In addition, a reference list and an appendix can be found at the end of this thesis. It includes relevant data such as the MATLAB code used for financial calculations.

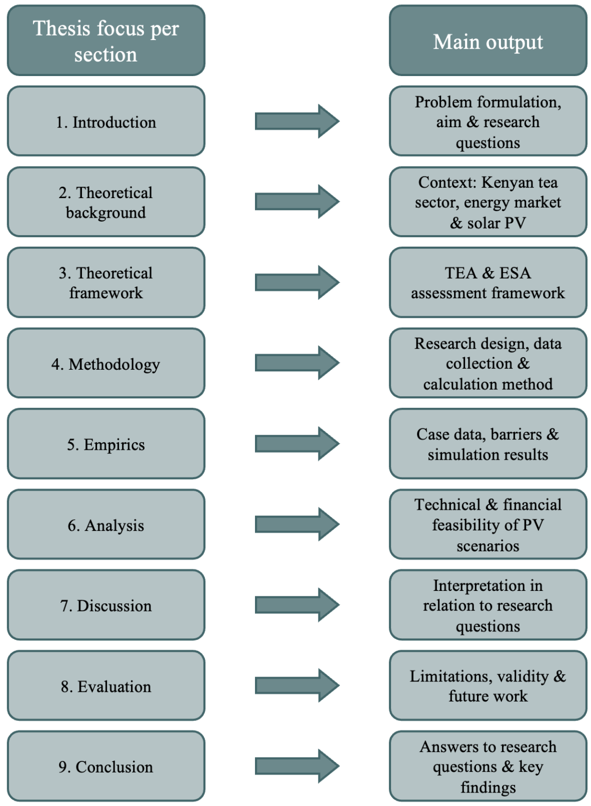


Figure 1: Overview of the report structure and the main outputs for each section.

Firstly, the introduction establishes the context for this thesis by outlining the role of the Kenyan tea sector, the current energy situation, the case company Miale, and finally, the aim, research questions and delimitations of the study. The following section, theoretical background, describes the Kenyan tea sector, the national energy market, and the role of solar PV technology in industrial applications, which is necessary information needed for understanding the analysis. Thereafter, the theoretical framework section introduces two frameworks that are used in this study for the assessment of solar PV feasibility: the Techno-Economic Analysis (TEA) and Energy Systems Analysis (ESA). Next, the methodology section describes how the study was conducted, including the research design, data collection process and calculation procedure. The empirical section presents findings throughout the study, including case factory data, current energy conditions, PV generation potential, identified barriers and incentives, the scenario inputs and financial results. After this, the results are further analysed in the analysis section. It evaluates the technical and financial feasibility of the different PV system scenarios, while also considering relevant barriers. The discussion then interprets all findings in relation to the research questions introduced in the introduction. Thereafter, the evaluation section evaluates and describes the limitations of the study, reliability, validity, generalization, and future work. Finally, the conclusion summarizes the main findings throughout the study and answers the research questions.

2 Theoretical Background

This chapter provides a background for understanding the thesis topics, including the Kenyan tea sector, the current energy system, and solar PV technology. It highlights key characteristics and trends in the sectors relevant to the research context. Together, this forms the foundation for analysing the feasibility of solar PV in tea manufacturing.

2.1. The Kenyan tea sector

Market overview

Kenya is ranked the third-largest tea producer in the world after China and India, with an average annual production of 585.5 million kg of processed tea between 2019 and 2024. During the same period, the production of green leaves increased by 25.6% as a result of favorable weather conditions, subsidized fertilizer, improved farm productivity and supportive input policies [14].

As of today, Kenya has over 180 tea processing factories with a combined capacity of processing over 2,700 million kg green leaves per year. 71 of the factories are operated by the Kenyan Tea Development Agency (KTDA) [15]. The total capacity output of processed tea, from all factories combined, is about 649 million kg annually, accounting for an average conversion from leaf to tea of 24% [14].

Key stakeholders within the sector

- **Kenyan Tea Development Agency (KTDA):** A private company owned by over 600,000 smallholder tea farmers across 16 counties in Kenya. KTDA accounts for about 60% of total tea production and thus plays an important role within the sector with several tasks, including the following [15]:
  1. **Smallholder management and processing:** KTDA manages the tea factories owned by the farmers and makes sure the green leaf collection, transport and the manufacturing process run smoothly. The total number of tea factories is currently 71, including 17 satellite factories established to handle increased leaf supply. The system is built to help the farmers produce and sell a high-quality product efficiently [15].
  2. **Logistics, input supply and farmer support:** The company is involved in logistics from farm to factory. It organizes the collection of green leaves to about a total of 3,200 buying centers, from where organized factory-owned trucks pick up the leaves and transport them to its factory [16]. In addition, KTDA supports the farmers by supplying them with bulk fertilizers, which lowers input costs and results in more stable farming for smallholders [17].
  3. **Extension services and trainings:** These roles are mainly done through Farmer Field Schools (FFS), a program that was introduced after a pilot project with Unilever's Lipton in 2006 [16].

It aims to teach farmers to improve productivity and quality through practical and group-based learning methods [17].

4. **Marketing and economic governance:** KTDA helps promote and market the smallholders' tea collectively for the benefit of its shareholders. Marketing is supported through services like warehousing, trading, packaging, distribution and financing, often through subsidiary operations such as Chai Trading Company Limited and Kenya Tea Packers Limited (KETEPA) [17].

- **Tea Board of Kenya (TBK):** A state corporation established under Section 3 of the Tea Act No. 23, 2020, with several key functions within the tea sector [18]:
  1. **Regulatory authority and licensing:** TBK registers, licenses and monitors different actors across the whole tea value chain. It also aims to protect farmers by monitoring unfair practices and overseeing the conditions for green leaf payments [18].
  2. **Industry development:** The corporation supports the socio-economic development of the sector by, for example, promoting value addition, supporting processing infrastructure, providing technical assistance and capacity building and coordinating research priorities. They aim to strengthen the industry while improving livelihoods for all people who depend on tea [18].
  3. **Market promotion and trade facilitation:** TBK aims to help Kenya maintain its global leading position within tea exports by promoting the country's tea in domestic and international markets [18].
  4. **Environmental and social governance:** TBK has set up a 2023-2027 Strategic Plan to take on a role to address challenges within sustainability and climate change. To mitigate against climate and weather variability, TBK has defined Climate-SMART Tea production as a central component in its Strategic Plan to integrate climate action and Environmental Social Governance (ESG) within the sector to ensure long-term sustainability and resilience [18].
- **Mombasa Tea Auction:** The world's second-largest tea auction by volume and the largest for Cutting, Tearing and Curling (CTC) teas. The key steps of the auction are [19]:
  1. **Auction coordination and price discovery:** The auction is operated by the East African Tea Trade Association (EATTA) and is held every Tuesday, bringing together producers, brokers, and buyers to trade teas. Producers include tea factories across Kenya and other East African countries. Brokers are engaged to taste and catalogue the teas for auction, while buyers evaluate them and bid competitively, resulting in determined market prices for East African tea [19].
  2. **Quality assurance and blending:** The purchased tea is sent to blending facilities, where quality testing is done to ensure correct flavors, moisture content, fiber levels and color grade. Grains from different origins and grades are then mixed for custom blends [19].
  3. **Packaging:** The final blends are packed based on their final destination [19].
  4. **Export and Documentation:** Several documents are required for exports. These documents include the Tea Board of Kenya export permit, Certificate of Origin, Phytosanitary certificate from

KEPHIS, Commercial invoice and packing list and Bill of Lading [19].

Manufacturing process for tea production

The tea manufacturing process that has been analysed in this study is CTC black tea. The structure of the process is similar across all CTC black tea factories in Kenya, resulting in generally comparable value chains, as visualized in Figure 2.

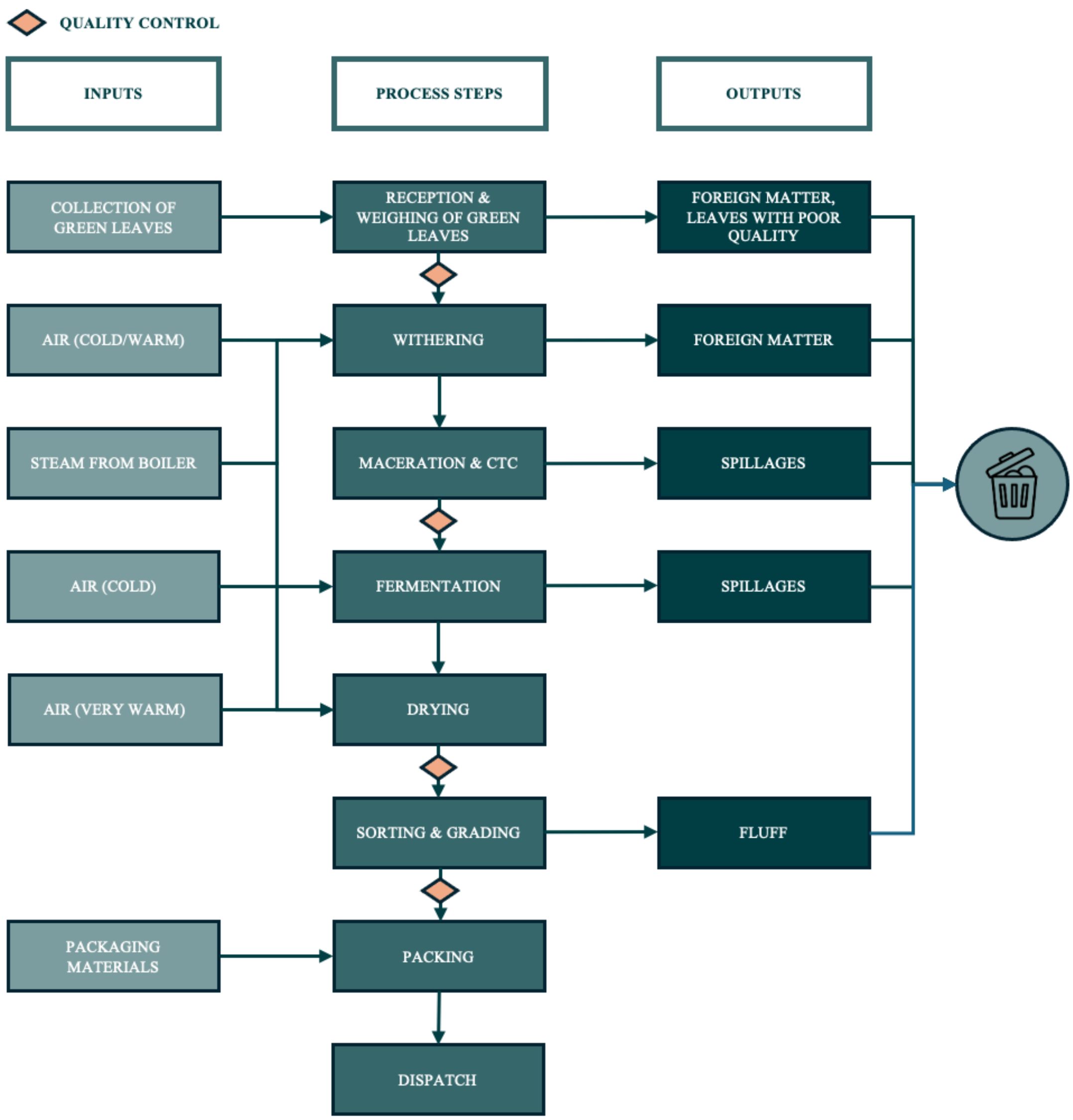


Figure 2: Flow chart of tea manufacturing process. Based on: [5].

1. **Green leaf reception:** To start with, green leaves are transported to a factory by trucks from several surrounding farmers. The trucks are weighed at the factory entrance to ensure the correct recording of the green leaves before processing. Once the leaves are received, a quality control is made to ensure the

leaves meet a certain standard [5].

2. **Withering:** After the leaves have passed the quality control, they are sent to the first processing step: withering. Withering is the biochemical and physical preparation of freshly plucked leaves. This step aims to change the chemical composition and physical properties of the leaf to ensure that it is prepared for further processing. Withering can either happen naturally or artificially. Natural withering takes about 12-18 hours and is affected by weather conditions and the withering area. Artificial withering, which is the most common technique used in factories, takes about 6-8 hours depending on the received volumes. In this process, the green leaves are spread out in several bins with connected fans driving hot air into it. The process is complete once the leaves reach a moisture content of about 65-67% [5].
3. **Maceration and Cutting, Tearing and Curling:** After withering, the leaves continues to the maceration and CTC process. In this step, fermentation is initiated as enzymes contact the substrate, triggering oxidative and fermentation reactions. The first stage of this process, maceration, is carried out using a rotor vane. Here, rotating and stationary metal blades are used to compress and shear the withered leaves entering. The second stage, CTC, is done in a series of three roller cutters. Once the leaves pass the rotor vane, they are sent to be cut into smaller, more uniform pieces. Then, they pass through two additional roller cutters for further processing, which gives the cut leaves the right form for proper fermentation. The final shape and size of the leaves are produced by specially designed roller teeth. The number of CTC lines depends on the factory and its size [5].
4. **Fermentation:** The next step in the manufacturing process is fermentation, which is the key stage in black tea production. After withering, the biochemical changes continue during fermentation, but at a faster rate, which causes major changes in the leaf compounds. This results in a change in characteristic taste, color and aroma of black tea. During the fermentation process step, the leaves lose their green colour and their grassy smell. Instead, it shifts to coppery red and brown soluble pigments due to oxidation of catechins and tannins. In addition, the bitter taste of the leaves is removed and replaced by a more mellow, pleasant taste. In modern production, this important step is usually an automated and continuous process. The air temperature and humidity are carefully controlled throughout the process, and the tea is regularly turned and mixed to ensure that the fermentation is even and that the product quality remains high. The controlled air is blown out through the fermenting bed to maintain optimal conditions [5].
5. **Drying:** After the fermentation, the leaves continue to the drying step. This is the last step in the process that alters the physical and chemical properties of tea. Hot air is blown by large fans through the fermented tea to reduce its moisture content. The tea grains are kept suspended during drying by fast-moving air in a process called fluidization. The process works as air is heated by large boilers, passed through the tea bed and then continues with a rich moisture content out through a chimney. Lighter particles, mainly dust, may be carried away due to the density differences of the tea particles and then recovered using cyclones. Maintaining the correct temperature is important during the drying

process, it needs to be high enough to stop fermentation quickly. If it's too low, it risks slowing down the drying and can prolong oxidation, resulting in reduced product quality. The moisture content of the tea is reduced from about 60% to about 3% during this step and takes about 25 to 30 minutes depending on the volume. The main purposes of drying are to first stop enzymatic reactions and oxidation, then to preserve quality, and lastly to remove moisture and ensure a stable product that can be transported and processed further [5].

6. **Sorting, storage and packing:** The final step, after the tea has been dried and stabilized, is to sort and pack the tea for dispatch. The tea is sorted by first removing dust and fibre. The methods used for this cleaning process is often cyclone separation and electrostatic extraction. After cleaning, the tea is sorted into different categories depending on the grain size. This is done by using multi-layer vibrating screens with different mesh sizes. The largest particles remain in the first grade, while the smallest particles move down to the last grade. The number of categories produced with different grain sizes varies from factory to factory, but each grade is often sold separately to suit different markets and consumer preferences. Before packaging, another quality control is made in a laboratory to ensure that the tea meets the desired quality. Lastly, after the tea has been sorted and passed quality control, it is stored in large sealed bins until there is enough for packing. Once ready, the tea is packed into waterproof, food-grade bags compacted to the correct density using a vibrant packing machine [5].

2.2. The energy market in Kenya

The market today

As of December 2025, the total installed electricity capacity in Kenya was 3,868.6 MW. This total capacity included 3,193.0 MW of installed interconnected capacity (connected to the national grid), 630.1 MW of captive capacity (private self generation for own use) and 45.5 MW of off-grid capacity [20]. Installed capacity refers to the maximum rated capacity, while effective capacity represents the capacity actually available under operating conditions. Kenya's total electricity capacity and its sources are presented in Table 1 below.

Table 1: Installed capacity in Kenya by technology in December 2025 [21].

Technology	Interconnected Capacity (MW)		Captive Capacity (MW)	Offgrid Capacity	Total Installed Capacity	% Total Installed
	Installed	Effective				
Geothermal	940.0	876.1	3.7	–	943.7	25.72%
Hydro	839.5	809.7	33.0	0.1	872.5	23.78%
Thermal	565.8	558.4	21.3	41.0	628.1	17.12%
Solar	210.3	210.3	326.7	3.9	540.9	14.74%
Wind	435.5	425.5	–	0.6	436.1	11.89%
Bioenergy	2.0	2.0	161.8	–	163.8	4.47%
WHRC[1]	–	–	83.5	–	83.5	2.28%
Imports	200.0	200.0	–	–	200.0	–
Total	**3,193.0**	**3,082.0**	**630.1**	**45.5**	**3,868.6**	**100.00%**

[1] WHRC = Waste Heat Recovery Cycle

As shown in the table, geothermal energy accounted for the largest share of installed capacity at 25.72% followed by hydro at 23.78% and then thermal at 17.12%. Solar PV contributed 14.74% and wind with 11.89%. Lastly, bio-energy capacity accounted for 4.47% and Waste Heat Recovery Cycle (WHRC) for the remaining 2.28% [20].

Following the installed capacity overview in Table 1, the electricity generation mix for Kenya's interconnected system is presented in Figure 3 below, based on the latest Energy & Petroleum Statistics Report covering July to December 2025.

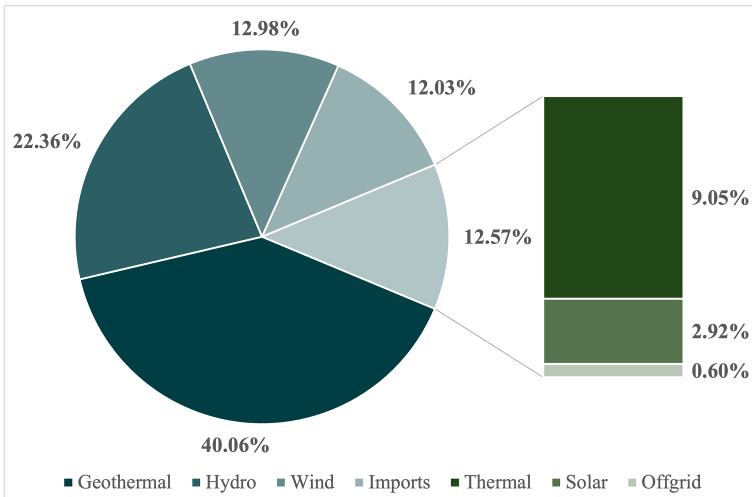


Figure 3: Kenya's energy mix within the interconnected sector in December 2025. Based on: [21].

Geothermal energy remains the largest source of electrical energy, accounting for 40.06% of the total energy generated within the interconnected energy sector. In the half year from July to December in 2025, 2,864.32 GWh of geothermal energy was generated, which is also an increase of 9.2% (263.44 GWh) compared to a similar period the year before. The increase is mainly due to a reduction in curtailment. Hydropower was the second largest energy source for the national grid, accounting for 22.36% of total generation. The output decreased by 2.31% (41.22 GWh) from the previous year between July and December, which was mainly driven by limited hydrology as a result of low precipitation. In third place, wind energy contributed with 22.36% of the total interconnected generation. This was an increase of 41.53 GWh, corresponding to 4.27%. The utility scale of solar PV generation fell marginally by 0.02 GWh from the previous half year in 2024 compared to 2025, representing 2.92% of total generation. Thermal generation, produced mainly from heavy fuel oil and kerosene, accounted for 9.05% of total generation and rose by 24.27% (138 GWh) in the same period of the previous year. The increase was mainly driven by higher daily energy demand. Finally, the strongest growth in any category was in electricity imports from Ethiopia and Uganda, with an increase of 24.9% (187.28 GWh). During the same period, Kenya had net exports of 136.55 GWh to Tanzania under the Ethiopia Kenya Tanzania wheeling arrangement and the Kenya Tanzania Energy Exchange Agreement [21].

The interconnected energy mix is used daily in Kenya and varies depending on the day and season. The country's daily demand profile is also affected by socio-economic activities in a daily cycle. The average daily demand profile for a weekday during the period between July 2024 and June 2025 is presented in Figure 4.

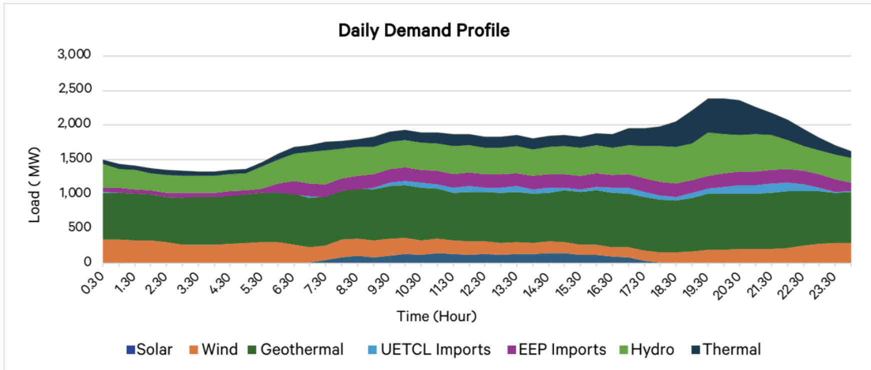


Figure 4: A typical demand profile for a regular weekday in Kenya. Obtained from: [20]. *UETCL Imports = imports from Uganda Electricity Transmission Company Limited, EEP Imports = imports from Ethiopian Electric Power.*

According to the daily peak demand figure, electricity demand in the Kenyan grid is the lowest between midnight and 05:00, typically reaching around 1,350 MW on weekdays and lower, around 980 MW on Sundays. Then, from 05:30, the electricity demand rises relatively quickly and reaches a morning peak of about 1,800 MW around the hour between 09:00 and 10:00 as daily activity begins. After the morning peak, the demand stays relatively stable throughout the day. Later in the afternoon, after 17:00, electricity demand increases sharply to a peak of 2,300 MW between 19:00 and 21:00, then gradually falls again. This daily demand pattern for a regular weekday is generally consistent throughout the week but can be affected by major, unpredictable power outages.

Even though the pattern for electricity demand is relatively similar for weekdays, the average total demand for each weekday during the review period 2024/2025 differs. The lowest total demand, except for Sundays, is on Mondays with a total of about 38,002.81 MWh. The demand then increases and peaks on Wednesdays where the average total demand is around 41,011.49 MWh. The demand then gradually decreases again until the weekend [20].

Future outlook

Kenya's plans to achieve a reliable, affordable and environmentally friendly energy system for the power sector are outlined in the Least Cost Power Development Plan (LCPDP) 2024–2043. The main strategy of the plans is to transition fully to clean energy by scaling up renewables to be able to meet the country's medium-term clean energy vision by 2030 and then the long-term net-zero goal by 2050. The country's forecast for the power sector considers three scenarios: the reference scenario, the vision scenario and the low scenario.

- The reference scenario is based on historical trends and expected growth in key demand drivers, national economic development and chosen committed flagship projects.
- The vision scenario assumes faster development, which is driven by Vision 2030 growth outlook and the implementation of flagship projects.
- The last scenario, the low scenario, represents the case with a low growth path where many of the government's plans aren't implemented as planned. It assumes no significant increase of economic development over the planning period.

Geothermal power is expected to remain the primary source of base load power for each scenario. The plans also include integrating modular nuclear technology to ensure long-term adequacy and diversity in the power sector. The capacity of nuclear power is projected to come in 2033 under the vision demand scenario or 2034 in the reference scenario. By 2043, Kenya's electricity mix is expected to consist solely of renewable sources, nuclear power and imports, and all diesel and gas-oil power plants are expected to be decommissioned by 2035. The plan is to have emissions below 0.5 Metric Tonnes of Carbon Dioxide Equivalent (MtCO2e) across the three planning scenarios [9].

2.3. Solar Photovoltaic systems for industrial applications

An overview of the system

A solar power system consists of several components to ensure efficient electricity production from the solar arrays, reaching the solar cells. The main components of a grid-connected solar power plant are the following:

- **Solar Photovoltaic panels:** Monocrystalline solar PV panels are commonly used for large industrial plants with high electricity demand. The size and number of cells are based on the load [22].
- **Inverter:** These are used to transform Direct Current (DC) into Alternating Current (AC). The number of inverters and their sizes are determined by the number of solar panels [22].
- **Grid connection:** These connections include substations and other associated components such as meters, transformers and protection devices [22].
- **Cables:** Cables are used on both the DC and AC sides of the system, with specifications depending on voltage, current and safety requirements. The PV arrays are connected to the inverters on the DC side, while the inverters are connected to the grid on the AC side [22].
- **Industrial load:** The solar system is connected to a load, represented here by a tea factory in Kenya.
- **Battery Energy Storage System (BESS):** A BESS system can also be connected to a grid-tied PV system. The battery can be used to store surplus electricity from the PV panels for later use [23].
- **Charge controller:** Controllers regulates the charge and discharge process to ensure the battery lifetime remains long. An inverter is also used to convert DC into AC electricity [24].

A general architecture of a solar power system with an industrial load and a BESS is presented in Figure 5.

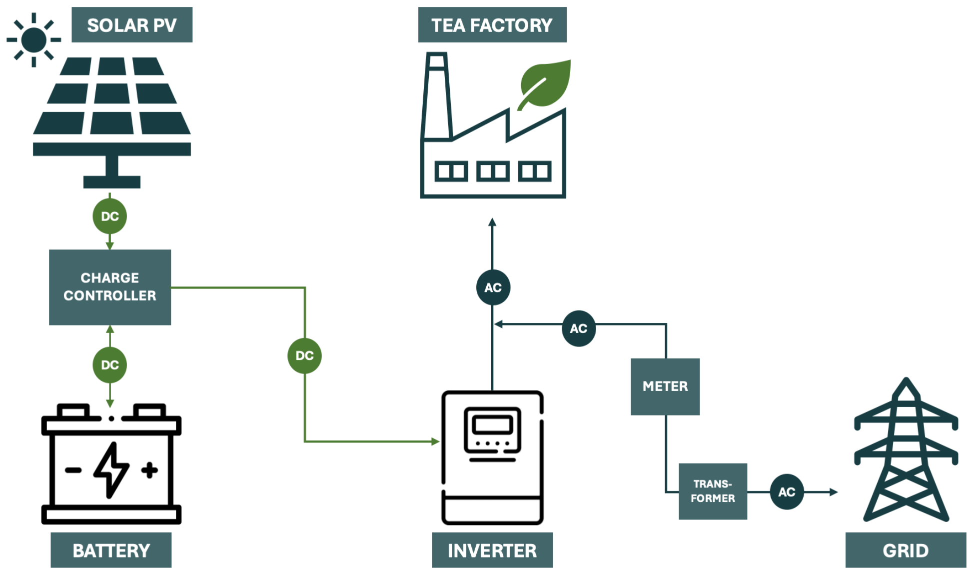


Figure 5: Schematic diagram of grid-connected solar PV system components with or without battery storage. Based on: [22], [24] & [23].

Factors that affect the solar panels' performance

The performance of solar PV panels depends on environmental conditions, panel characteristics and the design of the system [25].

One of the most important parameters is solar irradiance, meaning the intensity of solar radiation reaching the surface of the panel. Higher solar irradiance results in more generated electricity. Closely related to irradiance is solar insolation, which describes the total solar energy received over a specific period, often expressed as daily or annual values. This makes it useful for estimating a site's solar energy potential. Another key factor is the module temperature. Since converting solar energy to electricity results in excess energy in the form of heat, the temperature rises. This temperature increase leads to reduced open circuit voltage and lowers the maximum power output, affecting the overall performance negatively [25].

Shading is an additional factor that has a big impact on the system performance since it can cause a significant reduction in power output [25]. As a general rule, the panels should be placed at least twice the height of nearby objects to minimize the risk of shading during the four hours before and after noon. In addition, a smaller tilt angle results in less shading between rows and optimizes the available area. Similarly to shading, soiling, such as dust and dirt on the surface of the panels, can block sunlight from reaching the cells, generating a lower output. Strategic location and regular cleaning are key solutions to preventing these causes [26].

The angle of inclination and orientation of PV panels are additional factors strongly affecting daily and monthly power output since they regulate how much direct sunlight will reach the panels. A solar panel's optimal performance occurs when its surface is perpendicular to the sun, so an optimized system should be angled to account for this. For fixed installations, the system angle should thus be decided depending on local weather patterns at the installation site [26].

At the system level, inverter efficiency and Maximum Power Point Tracking (MPPT), are also important. A more efficient inverter reduces energy losses during conversion, while MPPT ensures optimal operating conditions under varying irradiance and temperature conditions. Other influence factors, such as cable losses, module mismatch, and system layout, also affect performance but are not as significant as the ones mentioned above [25].

Introducing the chosen components for the solar power system

The PV solar system chosen for this study is based on the JA Solar JAM72D30 550/MB module, which is a p-type double glass bifacial module [27]. Bifacial refers to the ability of a panel to absorb sunlight and generate electricity from both sides (front and back), thereby increasing power output [28]. This feature will not be considered in this study since the system Miale Solar uses for installations is monofacial, meaning that the panels only absorb sunlight and convert it to electricity on the front side. The simulations for the PV systems are based on the JAM72D30 550/MB module, but are limited to the monofacial feature [27].

The electrical characteristics of the panel under Standard Test Conditions (STC) are key reference values that influence system performance. The module's rated maximum power (Pmax) is 550 W, its open circuit voltage (Voc) is 49.90 V, its maximum power voltage (Vmp) is 41.96 V, the short circuit current is 14.98 A and its maximum power current is 14.03 A. The module conversion efficiency, referring to the conversion of incoming solar radiation into electrical energy, is 21.3%. The panel's dimensions are 2278±2mm × 1134±2mm × 30±1mm and have a total weight of 31.8 kg. It is designed to operate at a maximum system voltage of 1500 V and temperatures ranging from -40°C to +85°C [27].

Combined with the PV module, a three phase smart string inverter with the product name Huawei SUN2000 30KTL US is used in this study. The inverter has a rated output of 30 kW and a maximum efficiency of 98.6%. The inverter has a DC input voltage up to 1000 V and a MPPT voltage that ranges between 250 to 950 V. The number of MPP Trackers is three and the string inputs are six, which effectively reduces string mismatch. The inverter delivers a power output of 480 V and 60 Hz on the AC side, and has several integrated protection and monitoring features to ensure safe and reliable operations within the system. The product weighs 57 kg in total and has the dimensions 770 × 550 × 281mm [29].

For one scenario analysis in this study, a Battery Energy Storage Solution was used. The chosen BESS solution was the RCT Power CESS 200 PowerStone, a commercial and industrial outdoor-rated all-in-one cabinet storage system. With a nominal capacity of 233 kWh and a usable capacity of 217.9 kWh, the system is designed for large-scale energy storage applications requiring reliable and continuous power supply. The battery has a Lithium Iron Phosphate ($LiFePO_4$) chemistry and is rated for a battery life cycle of ≥ 6,000 full cycles at 25°C. In addition, the battery has 100% Depth of Discharge (DOD) and its State of Health (SOH) and end-of-life is rated 80%. These technical factors makes it suitable for commercial applications with a daily charging pattern. The CESS 200 PowerStone has a modularized AC/DC inverter with a rated AC and DC power output of 125 kW each, and a peak inverter efficiency of 98.5%. The battery has the dimensions of 1,100 × 2,300 × 1,340 mm and weighs approximately 2,700 kg [30].

All relevant technical specifications for the three components used in this study are summarized in Table 2.

Table 2: Summary of technical specifications of the selected components.

Parameter	**PV module: JA Solar JAM72D30 550/MB**	**Inverter: Huawei SUN2000 30KTL-US**	**BESS: RCT Power CESS 200 PowerStone**
Technology/type	p-type double glass bifacial[1]	Three-phase smart string inverter	All-in-one outdoor cabinet BESS
Rated power/output	P_{max}: 550 W	30 kW	125 kW (AC/DC)
Nominal/usable capacity	—	—	233 kWh / 217.9 kWh
Efficiency	21.3%	98.6%	98.5%
V_{oc} / V_{mp}	49.90 V / 41.96 V	MPPT: 250–950 V	DC voltage: 715–928 V
I_{sc} / I_{mp}	14.98 A / 14.03 A	—	—
Max. DC voltage	1500 V	1000 V	832 V (rated)
AC output	—	480 V, 60 Hz	400 V, 50/60 Hz
Battery life cycle	—	—	≥6,000 cycles @ 25°C, 100% DOD, 80% SOH
Operating temperature	−40°C to +85°C	−25°C to +60°C	−25°C to +45°C
Dimensions (mm)	2278 × 1134 × 30	770 × 550 × 281	1100 × 2300 × 1340
Weight	31.8 kg	57 kg	≈2,700 kg

[1] The selected PV module is bifacial, but only monofacial operation is considered in this study.

Operating conditions in Kenya

Due to Kenya's geographical position at the equator and its abundant insolation levels between 4 to 6 kWh/m^2 per day, the country has great potential to utilize solar energy throughout the year. Kenya's total solar generation potential is approximately 15 GW, and is pointed out as one of the global leading countries in solar energy potential [9].

As of today, around 200,000 PV solar home systems are in operation in Kenya. The majority are small systems rated between 10 to 20 watts of electrical power and primarily used for electricity to lighting and powering television. The cost for these systems is approximately 7.7 USD/W and generates 9 GWh of electricity together per year, representing about 1.2% of Kenyan household consumption. This number is expected to rise significantly, especially in rural areas where four million households are currently without these systems. As rural electrification is evolving and expanding and solar energy production costs are reduced, solar PV systems are expected to play a significant growing role in supplying households with electricity, water heating and telecommunications infrastructure in remote areas. According to the International Energy Agency (IEA), solar PV energy is expected to contribute with the largest share, about 47%, of the mix of technologies for both mini-grids and off-grid power systems in Sub-Saharan Africa by 2040. Even though it is a very important evolving energy source, it risks threatening the conventional utility market since the growth most likely will result in more consumers shifting away from grid-supplied electricity [9].

Figure 6 illustrates a map with the estimated potential solar PV generation in different areas in Kenya. The map represents an average daily and yearly electricity production based on a grid-connected solar PV system with peak generation of 1 kW. The data is based on a total period of 25 years from 1994 to 2018. The solar PV system consists of fixed ground-mounted crystalline silicon PV panels with a tilt of 0° to 12° toward the equator with high-efficiency inverters. The output data is from Solargis and accounts for expected losses and assumes 100% plant availability [31].

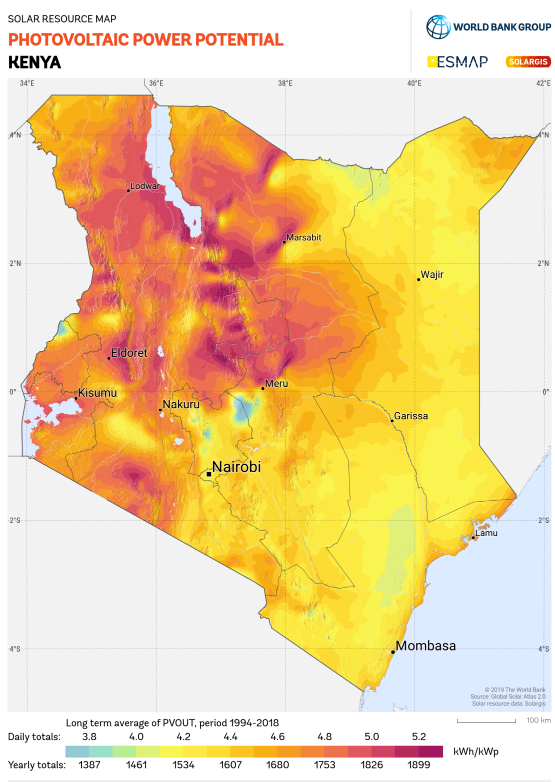


Figure 6: Map of solar PV power potential in Kenya's landscape. *kWh/kWp: kilowatt-hours produced per installed kilowatt-peak of solar PV capacity* Obtained from: [31], CC BY 4.0.

3 Theoretical Frameworks

This chapter presents the theoretical frameworks used to structure the analysis of solar system feasibility. It introduces the key concepts and parameters that guide the assessment. These frameworks are later applied to interpret the empirical findings and support the overall analysis.

3.1. Framework decision and functional unit

This report will assess the techno-economic feasibility of solar PV energy for sustainable tea production in Kenya based on the Techno-Economic Analysis framework (TEA) and the Energy Systems Analysis (ESA), as described in 3.2 and 3.3.

A functional unit is required for the TEA and ESA frameworks to ensure objective comparison across different products, technologies and processes [32]. The functional unit will serve as a reference quantity, and should be convenient, meaningful and have practical relevance to the final application. For this report, 1 kWh is the functional unit for energy measures. This unit allows for easy and objective comparison of scale, efficiency and cost, and any data given with different units will be converted to match it.

3.2. Techno-economic analysis framework

Introducing the TEA framework

The Techno-Economic Analysis framework is a recognized method for evaluating technical viability and economic feasability of a process or technology [33]. In broad terms, a TEA provides an estimate on cost, performance and emissions related to a specific process, and thus allows for comparison between key metrics of process feasability for different technology options [34]. It is often used for assessing and comparing current and considered technologies, to support investment decision-making and prioritize changes and operational development actions [35]. There are different approaches to TEA, depending on industry, process, technology and aim, and there are multiple metrics to consider to achieve valuable insights and provide reliable results [33].

A common approach is to divide the TEA into two main phases: a technical analysis and a financial analysis. While the technical analysis considers technical and operational constraints and requirements, it also functions as a foundation for the financial analysis [34].

For this report, the following steps and metrics have been decided as most important, and the described structure represents the general framework that will be used to complete the Techno-Economic Analysis on the feasibility of solar energy for tea production in Kenya:

1. **Technical analysis:**
   1.1. **Define system boundaries and desired level of precision:** System boundaries should be set to ensure the TEA will be performed on a clearly defined design basis that represents the relevant processes and components, while ensuring complexity remains at a minimum. The optimal level of precision depends on the development of the considered technology and process, i.e., what technical data is available, and the intended use of estimated cost and performance values [34].
   1.2. **Flow chart:** To ensure a holistic operational overview, a flow chart should be developed with descriptions of each major process step within the system boundaries. The flow chart maps out operational steps and connects them via feed streams, e.g., material addition or changes of surroundings [34].
   1.3. **Deciding design specifications, key metrics and assumptions:** Based on the process flow chart, the required design specifications for each operational step and feed stream should be decided. Design specifications are metrics based on data (either generic or measured) that can be used as inputs for calculations and process simulations. The required specifications depend on the system boundaries and the precision requirements, as described in 1.1. [34]. Key operational constraints and requirements, such as energy consumption, temperature limits, and utility availability, as well as assumptions on e.g., required operating hours and expected asset lifetime, must also be specified. These assumptions determine equipment sizing and system integration, and therefore directly influence capital and operating cost estimates. Moreover, they are crucial for either confirming or deterring the technical feasibility of integrating the new technology in manufacturing [36].
2. **Financial analysis**
   2.1. **Capital Cost:** When assessing financial aspects of a process or technology, Capital Expenses (CapEx) is a critical metric [33]. It refers to the non-recurring facility costs related to a project, such as the procurement of manufacturing equipment and construction. To ensure CapEx is measurable and comparable to other financial metrics, the TEA framework considers these costs as amortized over the asset's lifetime [32].
   2.2. **Operational Cost:** Another important metric for the cost analysis is the Operational Expenses (OpEx), which refers to recurring costs related to a process or technology, such as labor, energy and material. OpEx can be divided into fixed and variable, which must both be considered. Fixed Operating Costs do not vary with production output and include, e.g., labor cost and interest, while Variable Operating Costs include, e.g., material costs that are directly related to the production volume. The fixed operating costs over a period of time must therefore be divided by the volume of functional units produced over the same period, while variable operating costs can be directly connected to one functional unit [32].
   2.3. **LCOE:** For energy production technologies specifically, a critical metric is the Levelized Cost of Energy (LCOE), which estimates the cost of electricity per kWh produced over the life of a

generating plant [37]. As long as the discount rate and expected lifetime of the plant is known, LCOE for an solar generation system can be calculated as:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_0 (1-d)^{(t-1)}}{(1+r)^t}} \quad (1)$$

where

I_t = investment expenditures in year t

M_t = operations and maintenance expenditures in year t

F_t = fuel expenditures in year t

E_0 = Initial energy produced

d = degradation rate

r = discount rate, i.e., a financial metric used to determine the present value of future cash flows [38]

n = expected lifetime of the energy system

For the battery energy storage system, the cost per kWh is calculated based on CapEx, OpEx, efficiency losses and battery lifetime, as well as replacement requirements, distributed over the total electricity discharged during the assessment period. It includes both the cost of storage and the cost of discharge.

2.4. **AEP:** The Average Electricity Price (AEP) sums up the cost of electricity from all different sources (e.g., solar system, battery discharge, diesel, grid electricity) and divides it over the total electricity consumption over a year. The result is a case specific cost per unit of electricity, USD/kWh, used to assess how the overall cost varies with different energy setups. Therefore, it includes all costs related to the different energy sources. It is calculated based on specific consumption patterns, where the electricity consumption of a specific point in time is allocated to the actual corresponding electricity source. For this report, it is used as one of the main metrics when comparing financial feasibility from the consumer perspective, since it represents the overall cost of electricity in any potential scenario and setups. The formula for this metric would vary between different energy systems, but for this thesis AEP is calculated as:

$$\text{AEP} = \frac{E_{PV} \cdot LCOE_{PV} + E_{battery} \cdot LCOE_{battery} + E_{grid} \cdot C_{grid} + E_{diesel} \cdot C_{diesel}}{E_{total}} \quad (2)$$

Where (E) indicated the consumption from a source of electricity in kWh and (LCOE) and (C) indicated the cost per kWh of electricity from the corresponding source. In the scenario where Net Metering is assumed possible, the earnings per kWh is also considered.

2.5. **Investment appraisal:** Beyond the costs, there are other financial metrics to consider when evaluating the economic feasibility and allure of an investment. Typical methods used for investment appraisal are Net Profit Margin (PM), Net Present Value (NPV), Internal Rate of

Return (IRR), and Payback Period (PP) [39]. These metrics can be calculated or solved from the following formulas [40][41][42]. :

$$PM = \frac{\text{R} - \text{COGS} - \text{E} - \text{I} - \text{T}}{\text{R}} = \frac{\text{Net income}}{\text{R}} \tag{3}$$

$$NPV = \frac{\text{Cash Flow}}{(1+i)^t} - \text{Initial Investment} \tag{4}$$

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0 \tag{5}$$

$$PP = \frac{\text{Cost of Investment}}{\text{Average Annual Cash Flow}} \tag{6}$$

where

R = Revenue

$COGS$ = Cost of goods sold

E = Operating and other expenses

I = Interests

T = Taxes

i = required return or discount rate

t = number of time periods

C_t = Net cash inflow during the period t

C_0 = Total initial investment cost.

In general, a project or investment should be accepted if:

- NPV is positive [40],
- and IRR is larger than the Cost of Capital [41].

However, other factors such as fund limitations or external risks (political, environmental etc.) may influence investment decisions.

3. **Evaluation**

3.1. **Technical evaluation:** The technical evaluation assesses whether a technology or process can realistically and reliably meet the operational requirements of manufacturing operations under the defined system boundaries, design specifications, and assumptions. This step determines whether the technology is even technically feasible, before economic viability is considered. A technology or process can be considered technically feasible if it meets the defined functional requirements, operates within technical and regulatory constraints, integrates into the intended context, and maintains operational stability [36]. Only then should it proceed to economic evaluation [34].

3.2. **Financial evaluation:** In terms of economic feasibility, the most critical metrics and evaluation results may vary depending on the situation, between the supplier and the customer, as well as between different financing models. In general, it is built on a combination of the metrics described in 2.1-2.4, in section 3.2.1. However, the capability of investment for outright purchase is highly dependent on the liquidity and cash flow of the investor. Even when the costs and appraisal metrics is favorable, the requirement for a large upfront payment may ultimately determine the possibility to invest [32], [35].

Techno-Economic Analysis for Solar Photovoltaic systems in industrial tea manufacturing

For this report, the TEA framework will be used to evaluate the feasibility of installing Solar PV cells in the tea industry. The process or technology assessed is thereby the PV energy system, and its application within industrial tea manufacturing.

1. **Technical evaluation:** The technical evaluation aims to explore the ability of the solar PV energy system to supply the tea factory with the energy required to meet its consumption demand. Within a tea factory, there are multiple ways to define system boundaries for an energy system. There are both direct energy consumption within the manufacturing process, from running the industrial equipment and machines, and indirect consumption within the facility, e.g. for lights. For this report, the system boundary is drawn to include the entire electricity consumption of the tea factory, both direct manufacturing consumption and indirect consumption. However, the energy system must not necessarily cover the entire consumption within the system boundary. It can either be scaled down to optimize utilization, or scaled up to cover peak load (and potentially be combined with a Battery Energy Storage System). Beyond total electricity consumption, design specifications that must be considered in a tea factory include manufacturing hours, energy consumption patterns, energy generation (based on weather data), and physical design constraints and facility features (e.g. available roof area for installing the PV cells).
2. **Financial evaluation:** The financial evaluation aims to explore the ability of the solar PV energy system to compete financially with existing energy supply systems, particularly the national grid.
    - **Supplier Perspective / Outright Purchase:** For a financial evaluation of an outright purchase of the system, the most critical metric for the supplier is the PM as described in 2.4 under 3.2.1, i.e. how much profit the project will generate for the business. For a solar PV system, CapEx includes the cost of purchasing and installing the actual hardware, e.g., PV cells, inverters, mounting equipment and (potentially) a BESS. With an outright purchase, the energy system supplier can purchase the hardware components and sell them at a higher price to the customer, with the service of designing and installing the PV system [11]. The margin that differences the purchasing price and the sales price accounts for the profit of the supplier. However, there may be other factors that influence the appeal of the project, such as customer attractiveness, funding availability etc.
    - **Customer Perspective / Outright Purchase:** Looking at an outright purchase of a PV energy system from a customer perspective, the financial evaluation is mainly based on assessing costs. The most important metric is the total AEP, meaning the average cost of 1 kWh for the factory. This presents a benchmark that allows for easy cost comparison between different energy systems -

will the AEP increase or decrease with the new system? However, the financial evaluation is not only based on a cost assessment, but on putting these costs in relation to direct earnings. This is where NPV, IRR and PP are used, to ensure the investment is financially defendable.

- **Supplier Perspective / Power Purchasing Agreement:** When considering a Power Purchasing Agreement (PPA), a lot of the financial risk is transferred from the customer to the supplier [13]. Investment appraisal metrics such as NPV, IRR and PP are critical to ensure the investment is financially beneficial for the supplier. Both CapEx and OpEx is covered by the supplier, and the profit margin between the $LCOE_{PV}$ (as calculated) and the discounted electricity price (described below) equals the earnings and suggests if the investment and agreement is financially defendable.
- **Customer Perspective / Power Purchasing Agreement:** With a PPA, the AEP becomes the only critical metric for the customer. Since the capital investment and operational costs are fully covered by the supplier, the customer's investment is zero. The cost of electricity from the solar PV system, the discounted electricity price is given by the supplier as a discounted price from what the national grid charges. The AEP is then calculated by using this price instead of the $LCOE_{PV}$.

3.3. Energy Systems Analysis

An ESA was used during this study to understand different energy system setups and how they interact with the hourly electricity demand in medium-sized Kenyan tea factories. While the techno-economic framework evaluates the financial feasibility of each PV system, the ESA can be used as a technical basis for the financial calculations by providing information on how electricity can be generated, consumed, stored, exported, or purchased from the grid over a time period.

In this study, the ESA is based on the PV system modeling and simulations conducted by Vilma Delden [43]. The technically feasible PV systems identified by Delden were used as a foundation for the financial calculations defined in section 3.2.1. The modeling framework used in Delden's study was based on a combination of System Advisor Model (SAM) (version 2025.4.16), PySAM and Python calculations, where each system had its own purpose. SAM was primarily used to model the performance of different PV systems while also generating hourly energy flow outputs. PySAM, which is the Python interface for SAM, was used to adjust input parameters and run multiple simulations automatically, while preserving the same model structure as in SAM. Lastly, Python was also used by Delden for the sensitivity analysis and to model battery dispatch patterns. The weather data used for all these simulations were downloaded from PVGIS in EnergyPlus Weather. This data was used as an estimated basis of hourly meteorological conditions in the analysed regions.

The ESA framework is relevant for this study since optimized solar power systems not only depend on the total electricity production, but also on how well the production matches the electricity demand of the load. The ESA basis will be further used for this study's simulation and calculation procedure described in section 4.3.5.

4 Methodology

This chapter describes the research design and methodological approach used in the study. It outlines how data was collected and analysed, and discusses the reliability and validity of the chosen methods in relation to the research question.

4.1. Research methodology

There are several different methods for conducting research, and the overarching purpose of this study is both exploratory and problem solving [44]. The data gathering was completed with a mixed-methods approach as described in chapter 4.2.1, including both qualitative and quantitative data [45]. The research addressed two independent subject areas; the tea manufacturing industry and solar PV technology. The exploratory elements of the research were conducted to increase the general understanding of both research topics. The problem solving elements aimed to assess the findings of the explanatory study to answer the research topics.

Flexible case study

Based on the purpose of this thesis, a flexible case study was determined to be the most suitable methodology for problem solving. A case study approach enables an in-depth assessment of both research subject areas within their specific context, as well as combined. In this case, it allows a deep assessment on the current situation, goals and possibilities for solar energy within the Kenyan tea manufacturing industry. This includes not only technical parameters, but also operational and organizational practices, decision-making processes and priorities, and external factors such as policy and market conditions. The research techniques used were:

- Semi-structured interviews and correspondence
- Observations during site visits
- Analysis of quantitative data as acquired
- Simulations and calculations

Due to the exploratory elements of the research and the project plan as a whole, the type and amount of data that would be collected was not known in advance. Consequently, the research design required flexibility to enable incorporation of insights gained during the data collection process. The flexible method allows for progressive adjustment and refinement of the direction of research as well as assumptions and modeling parameters throughout the research process [44]. This is highly relevant in techno-economic assessments, where both input data and modeling parameters may evolve as new information becomes available.

Case object selection

Based on the data gathered during the field study in Kenya, case objects could be selected. The chosen case objects are split into two categories; customer and supplier.

For the *customer* perspective, the case study is conducted over a number of tea factories, split into different categories based on geographical location and factory size. A total of 70 factories owned and managed by Kenya Tea Development Agency has been considered for the study. These have been divided into two core geographical areas; West and Central, and three size groups based on finished product output; Small, Medium and Large. A more detailed description of this categorization is provided in Section 5.1. Based on these groupings, average values of key parameters, e.g., energy consumption has been calculated and used for the analysis. This is not the conventional method for a case study, but given this setup, the results can be considered more general and applicable over the whole industry, compared to if only one case factory was selected [44].

For the *supplier* perspective, Miale Solar was chosen as the only case object. Conducting the case study from Miale's perspective allows an assessment on supplier potential in supplying the solar energy systems to the chosen case customers, from a techno-economic perspective. Moreover, this allows for a natural setup of design parameters for simulation and otimization of the energy system, as Miale already operates with certain hardware components. All simulations and calculations were conducted based on the specific hardware that Miale uses in their projects.

Overall, the flexible case study methodology and chosen case objects support a comprehensive and context-sensitive evaluation of the techno-economic feasibility of solar energy systems in Kenyan tea factories.

4.2. Research approach and method design

Mixed-methods approach

Given the nature of the research problem, that demands assessment of two independent subject areas through a methodology that is both exploratory and problem solving, a mixed-methods approach was identified as most suitable for the project design. Specifically, a concurrent mixed-methods strategy was used, in which quantitative and qualitative data has been converged to provide comprehensive results on the techno-economic feasibility for solar PV energy systems within the Kenyan tea industry [45].

Qualitative strategies

Qualitative data is information made up of words and descriptions that cannot be measured, counted, or calculated. It requires analysis through categorization, sorting and evaluation. The data gathering process included interviews and observation as described in section 4.3.1 and 4.3.2 [44].

Quantitative strategies

Quantitative data is data represented by numerical values or counts. It can be classified and analysed through static methods - calculations of e.g., average values and spread, diagrams and plots [44]. As described in section 3.3, the quantitative data in this report has been processed and analysed and used as input in simulations and calculations on the solar PV system design and for the financial evaluation. Calculations were made to compute all key financial metrics for the Techno-Economic Assessment. The MATLAB code used can be found in Appendix 9.1.

4.3. Data gathering

Observations

During the two month field study in Kenya, part of the data gathering was performed as direct observation during study visits to tea factories. The objective was to gain insights for the exploratory parts of the research project, specifically on the tea industry - the manufacturing process and energy systems in use. Moreover, it gave initial impressions on the feasibility for installing solar PV systems. Over the field study period, a total of three site visits were completed to three different tea factories where the researches acted as participating observers during factory tours, open discussions and interviews (as described in 4.3.2). The names of the visited factories will not be published in this report to protect sensitive data, but will be referred to with a number, as presented below:

- **Factory 1:** Region Central, privately owned and managed
- **Factory 2:** Region Central, KTDA owned and managed
- **Factory 3:** Region Central, KTDA owned and managed

The observations made during site visits were essential mainly as a tool to find interesting and relevant research topics, questions and areas of importance. Moreover, visiting the factories and talking to representatives in the industry gave a broader understanding of both barriers and incentives for transitioning to solar PV, further discussed in chapter 5.3.

Interviews and correspondence

Another key method for gathering qualitative data, both for exploring and problem solving within the project questions, was conducting interviews and correspondence with relevant stakeholders. A total of 17 interviews and one email correspondence were conducted, as presented in table 4.

Table 4: List of conducted interviews

Industry	Company/Organisation	Position/Role	Date	Format	Length	Ref
Tea Sector	Factory 1	Electrical Engineer	2026-02-09	Interview on site	44 min	I1
Tea Sector	Elite Edge consulting	Chief Operational Officer (COO)	2026-02-25	Interview at office	41 min	I2
Tea Sector	KTDA[1]	Manager KTDA Power	2026-03-03	Interview at office	73 min	I3
Tea Sector	Factory 2	Factory Unit Manager (FUM)	2026-03-10	Interview on site	45 min	I4
Tea Sector	Factory 3	Production Manager	2026-03-27	Physical interview	34 min	I5
Tea Sector	TBK[2]	Ag. Director	2026-03-16	Interview at office	37 min	I6
Solar PV Sector	Soventix East Africa	Project Manager	2026-03-13	Digital interview	48 min	I7
Solar PV Sector	Miale Solar	Head of Engineer	2026-02-12	Interview at office	35 min	I8
Solar PV Sector	Miale Solar	Chief Executive Officer (CEO)	2026-02-17	Digital interview	50 min	I9
Solar PV Sector	Miale Solar	Chief Financial Officer (CFO)	2026-02-24	Interview at office	51 min	I10
Solar PV Sector	Miale Solar	Project Manager	2026-02-25	Interview at office	40 min	I11
Solar PV Sector	Miale Solar	Key Account Manager	2026-03-04	Interview at office	47 min	I12
Solar PV Sector	Miale Solar	Procurement and Supply Chain Officer	2026-03-18	Digital interview	35 min	I13
Energy	Ministry of Energy and Petroleum	Technical Advisor to Cabinet Secretary	2026-03-11	Interview at office	60 min	I14
Energy	Strathmore University	Engineer	2026-03-16	Email correspondence	–	I15
Energy	UNIDO[3]	National Project Coordinator	2026-03-24	Digital interview	35 min	I16
Energy	Swedish Energy Agency	Case Manager and Technical Advisor	2026-04-14	Digital interview	32 min	I17
Carbon Credits	Embassy of Sweden	Regional Climate Change and Environment Specialist	2026-03-13	Digital interview	38 min	I18
Carbon Credits	Embassy of Sweden	First Secretary	2026-03-13	Digital interview	38 min	I18
Carbon Credits	Sida	Lead Policy Specialist Environment and Climate Change	2026-03-13	Digital interview	38 min	I18

[1] KTDA = Kenyan Tea Development Agency
[2] TBK = Tea Board of Kenya
[3] UNIDO = United Nations Industrial Development Organization

Given the flexible method design, the list of stakeholders was continuously expanded as the study progressed, and list of interviewees was successively crafted to bring in multiple perspectives on both subject areas; the Kenyan tea industry and the solar PV technology, as well as on the Kenyan energy market. The interviews were semi-structured, meaning that a list of questions were used as a framework for the interview but that the order, phrasing and number of questions could be changed, and that follow up questions were asked if they occurred and the situation allowed for it [44]. The question framework was carefully crafted before each interview, and tailored for the particular interviewee. Key points of interests and topics discussed, depending on the role and industry of the interviewee, included:

- **Energy industry:** Domestic energy market (current and development), policy frameworks, energy politics, and regulatory aspects related to renewable energy in industrial applications.
- **Tea industry:** Manufacturing process, energy use, investment decision-making, and incentives related to transitioning to solar PV.
- **Solar PV sector:** Company strategy, project engineering and design process, technical and financial key parameters, and investment decision-making.

To ensure a holistic perspective with multiple points of view, and to triangulate facts and perceptions [45], some questions were repeatedly asked to different stakeholders. In alignment with the semi-structured interview format, open discussion was encouraged to allow for the interviewee to share important knowledge and insights that the interviewers may have been oblivious to beforehand. The interview length varied between approximately 30-60 minutes depending on the interviewee's role, knowledge and willingness to share. All interviews except [I14] were audio recorded, transcribed and refined to ensure a clean record was kept of what was shared. For the exception, notes were taken and later consolidated into a refined text. The consolidated interviews have been weighted equally as literature and written references, given the interviewees' roles and experience in their respective fields of expertise. In the report, information gathered from the interviews are referred to with a capital I and the corresponding reference number as presented in table 4.

Public qualitative data

To complement the data gathered from interviews and observation during the field study in Kenya, qualitative data has been collected from already published research, websites, documents and literature found online. An assessment on pre-existing frameworks and knowledge within the subject areas are important for the relevance of the thesis, as well as for the exploratory part of the research process. Existing qualitative data has been crucial in creating a holistic understanding on both the tea industry and the solar PV technology, and has been particularly important for building the theoretical background and theoretical framework. Moreover, the insights gained during this part of the research has been useful for identifying relevant research topics and prioritizing between focus areas, and thus deciding on method and specifying the overarching research questions of the study. The written sources used in this report is presented in the section *References*.

Quantitative data

The quantitative data gathered and used in this report was acquired either through public data sources or as a result of the interviews and correspondence as described in section 4.3.2. Public data used includes weather data, i.e., data on the solar irradiation on the chosen geographic areas, downloaded from Global Solar Atlas [31] and PVGIS through SAM. Technical and financial quantitative data on tea factories were shared by stakeholders met at interviews and during site visits. KTDA provided data on e.g., energy consumption, electricity bills, and finished goods output from 70 of their factories, which has been used as the main quantitative data source for assessing the tea manufacturing process. As mentioned in section 4.2.3, the data was processed to support analysis and simplify conclusion-drawing. The data was used to classify the case factories based on size (in terms of finished-product output), which was used to build the three size categories for the case study. Simple calculations were made to identify average values and spread, to later use as inputs in simulations and for financial analysis. Moreover, graphs were created to visually display key parameters and to get an understanding on how e.g., solar generation and factory load correlates.

Simulation and calculation procedure

As described in section 3.3, the Energy Systems Analysis (ESA) is a framework that provides a technical basis for evaluating how different system setups interact with hourly power demand from the tea factories. This section includes a description of how Vilma Delden's setup in SAM, PySAM and Python was used to generate energy flow outputs for financial calculations. To evaluate the financial feasibility of the different PV system configurations, MATLAB was used to calculate the financial metrics defined in section 3.2 for all technically feasible PV systems identified and dimensioned by Delden. The calculations were conducted for four different scenarios:

1. Base Case
2. Grid-tied PV system, without Net Metering and without Battery Energy Storage System
3. Grid-tied PV system, with Net Metering and without BESS
4. Grid-tied PV system, with BESS and no Net Metering

Each scenario will be further explained later in section 5.4.

For the base case, the factory electricity demand was assumed to be supplied entirely by the national grid: Kenya Power and Lighting Company (KPLC). Since the other calculations required detailed hourly data on system operation, the solar power systems were further simulated in SAM. The simulations were made for each system setup for every hour during a period of time. The SAM simulations provided the hourly energy flow data needed as input to the MATLAB calculations, making it possible to capture how each system interacted with the electricity demand, the national grid and, where applicable, battery storage.

For the two grid-tied PV system scenarios without BESS, these four chosen parameters were exported from SAM to Excel and subsequently used as input in MATLAB:

- Electricity load
- Power from PV system to load
- Power from PV system to the grid
- Power from the grid to the load

These outputs made it possible to distinguish between electricity consumed directly from the PV system, electricity purchased from KPLC and, in the Net Metering scenario, electricity exported to the grid. The simulations were conducted for every hour during one (the first) year.

In the last scenario, which included battery storage, additional energy flows were required to represent the battery's role in the system. To achieve this, battery dispatch patterns were first estimated through the Python-based simulations developed by Delden. These simulations modeled how each battery system would charge and discharge over time, providing the performance characteristics needed as inputs for SAM. Afterward, SAM was used to run hourly simulations of energy flows across all system configurations for the last presented scenario. The SAM outputs were:

- Electricity load
- Power from the PV system to the load
- Power from the PV system to the battery
- Power from the battery to the load
- Power from the grid to the load

These hourly values were used to evaluate how different battery sizes affected the use of solar electricity and the dependence on grid electricity. The simulations were conducted for every hour during 25 years.

The different simulation periods were caused by the structure of the SAM model used in this study. While scenarios with BESS could be simulated over the full 25 year project lifetime, scenarios without BESS only provided first year energy outputs. To ensure comparability, the first year results for the non BESS scenarios were projected over the same 25 year financial assessment period, using assumptions for PV degradation, system lifetime, component lifespans and long term cash flows.

After all simulations were done, the relevant economic metrics for all technically feasible systems in each scenario were calculated. All MATLAB scripts are presented in Appendix 9.1, and all input values used are defined in section 5.5.

4.4. Quality of research

Reliability

Typical measures to ensure qualitative reliability were used for this study, including double-checking interview transcripts for errors, cross-checking equations, functions and codes used in simulation as well as ensuring transparency between the researchers throughout the entire research process [45].

Validity

The key measures taken to in this study to ensure validity are triangulation, bias clarification, and peer debriefing [45]. Multiple check-ins with the project supervisor, Martin Andersson, were completed to allow for questions and discussion on the ongoing study. Moreover, the entire project was completed in collaboration with Delden, which ensured all gathered data was checked for accuracy by not only the authors but by another person.

4.5. Research ethics

Ethical aspects have been part of this research, particularly in relation to data collection, managing sensitive information, and the interaction with participants in Kenya. In accordance with established methodology guidelines, transparency, objectivity, and respect for participants have been highly prioritized in the study [44].

One important ethical consideration concerns the collection of qualitative data, particularly in terms of transparency and respect for participants. All interviewees were informed about the purpose of the study, how collected data would be used, and their voluntary participation. Participants were allowed to refrain from answering questions, or withdraw from the study at any point, as well as disallow audio recording. All interviews and site visits were conducted by at least two people, either both authors or one author and by Delden [43]. Furthermore, care has been taken to ensure all collected data was handled responsibly. Interview recordings and transcripts have been securely archived, and are used solely for the purposes of this study. The quantitative data acquired were requested via a written formal letter, where the purpose of the request was clearly stated. To protect sensitive information and ensure confidentiality, the names individual interviewees have been anonymised in the report. As described in section 4.3.1, factories are referred to using generic identifiers, and coordinates will not be published. When presenting empirical findings and results, information and data has been aggregated where appropriate. This due to the potentially sensitive nature of data shared during interviews and site visits, and to avoid identification of individual stakeholders.

Another important ethical consideration was objectivity. Given the collaboration with Miale Solar, efforts have been made to maintain an independent and critical perspective. Since no financial compensation was provided by Miale Solar, the researchers could avoid bias and ensure the purpose of the field study would remain solely academic. The main purpose of the collaboration was to get the supplier perspective on the research topics, and for the researchers to understand the situation, questions and priorities within the solar PV industry. Moreover, Miale Solar were helpful in acquiring contacts within the relevant industries in Kenya.

Finally, the study aligns with principles of good scientific practice by ensuring transparency in the methodology, referencing of sources, and clear acknowledgment of delimitation and potential biases. These measures combined ensure credibility and ethical integrity of the thesis.

5 Empirics

This chapter presents the empirical findings from the field study, including case-specific data, identified barriers and incentives, and simulation results. The findings are structured to provide a basis for the subsequent analysis.

5.1. Understanding the case factories

Within the industrial sector, Miale Solar has identified tea factories as a key opportunity for the integration of Solar Photovoltaics (PV). This is mainly due to the factories' large electricity consumption, while also facing increasing pressure to reduce energy costs and improve reliability. Interviewees [I9], [I10] and [I12] at Miale Solar described the cost of electricity as one of the main reasons for Commercial and Industrial (C&I) customers to consider solar PV, while power outages were mentioned as an additional operational concern. As of today, Miale has not yet implemented any solar PV projects at tea factories. However, [I9], [I11], [I12] and [I13] explain that the solar company has been involved in feasibility studies and is currently in dialogue with actors within the sector discussing potential future projects.

70 factories managed by Kenya Tea Development Agency (KTDA) were chosen as case objects for this feasibility study. Since tea factories are a part of a wider agricultural system, the electricity demand is not only regulated by installed equipment, but it is also heavily affected by production volumes, green leaf supply, weather conditions and operating schedules. Since these factors need to be considered, interviewees [I1], [I4] and [I5] explain that the manufacturing process in the factories can not be easily shifted to match hours with the highest solar generation. In addition to factory management structure, geographic location, production volume, and current energy setup, the load profile is therefore particularly important when assessing the technical and economic feasibility of solar PV.

KTDA Management

According to the KTDA Power Manager [I3], KTDA was previously known as the Kenya Tea Development Authority while it was government-owned. As of today, the organization is private and farmer-owned. Each of KTDA's factories is typically owned by around 8,000 to 15,000 farmers and the organization has a "farmer first" philosophy with the primary focus to improve farmer welfare. The ownership structure plays an important role in understanding the analysed case factories since investment decisions, energy costs, and long-term benefits are ultimately linked to the farmers who own the factories.

It is also explained by [I3] that KTDA Power was founded around 2010 with its own focus to support the tea factories with clean, affordable and reliable energy. This was particularly important since many of the regions, where the factories are located, are at the edge of the national transmission infrastructure, where voltage drops and grid instability are common. To address these challenges, KTDA Power acts by supporting energy projects at the factories through feasibility studies, procurement, construction, operations and maintenance. For example, the department had been involved in developing hydropower projects together with regional power companies at locations where groups of nearby factories are placed close to each other and a suitable resource, such as a river. However, there are still many factories that cannot be supplied by hydropower because of their geographic position, which has resulted in solar energy being an important part of KTDA's renewable energy strategy. The renewable energy committee has set goals within the strategy, which include replacing up to 70% of electricity needs with renewables, reducing electricity cost by 50% and replacing firewood within the next five years. KTDA aims to install 40 MW of solar energy within 2-3 years, which makes KTDA-managed factories relevant as case objects for assessing the technical and financial feasibility of solar PV within the wider factory network.

Distribution of factories by region and size

Geographical location and weather conditions

The 70 KTDA-managed factories analysed in this study are located in twelve different zones in Kenya. To get a better understanding of the potential operating conditions for solar PV systems, weather data was collected from Global Solar Atlas for each zone based on estimated appropriate coordinates. The average hourly profiles of Direct Normal Irradiation (DHI) [Wh/m^2] for each zone were plotted and are presented in Figure 7.

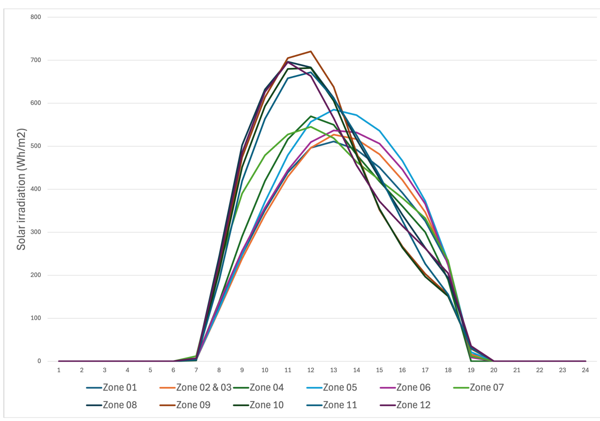


Figure 7: Direct normal irradiation [Wh/m^2] in each zone 1-12.

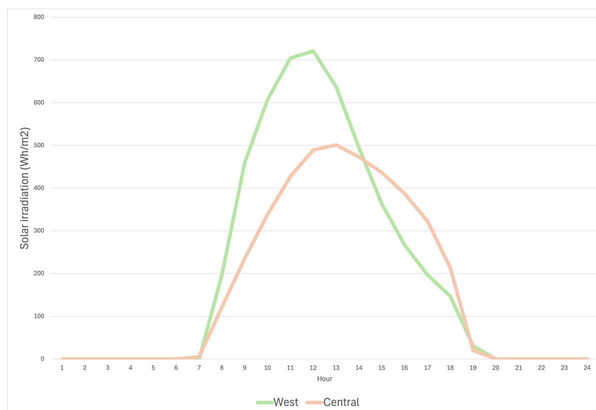


Figure 8: Average direct normal irradiation [Wh/m^2] in Region West & Central.

By analysing the graphs in Figure 7, two irradiation patterns stand out, one for the central zones (1-7) of Kenya and one for the western zones (8-12). Thus, the twelve zones could be divided into two grouped regions with one average common DHI pattern. The average DHI [Wh/m^2] in each region was plotted and is presented in Figure 8. The data is based on weighted coordinates and downloaded from Global Solar Atlas [31].

All twelve zones and their coordinates (marked red) were illustrated by using an AI tool and are presented in Figure 9 below. The central zones 1-7 are marked orange, while the western zones 8-12 are marked green. The weighted average coordinates used for plotting DHI data in Figure 8 is also marked out as stars, -0.495789°, 35.157861° for Region West and -0.566541°, 37.246373° for Region Central.

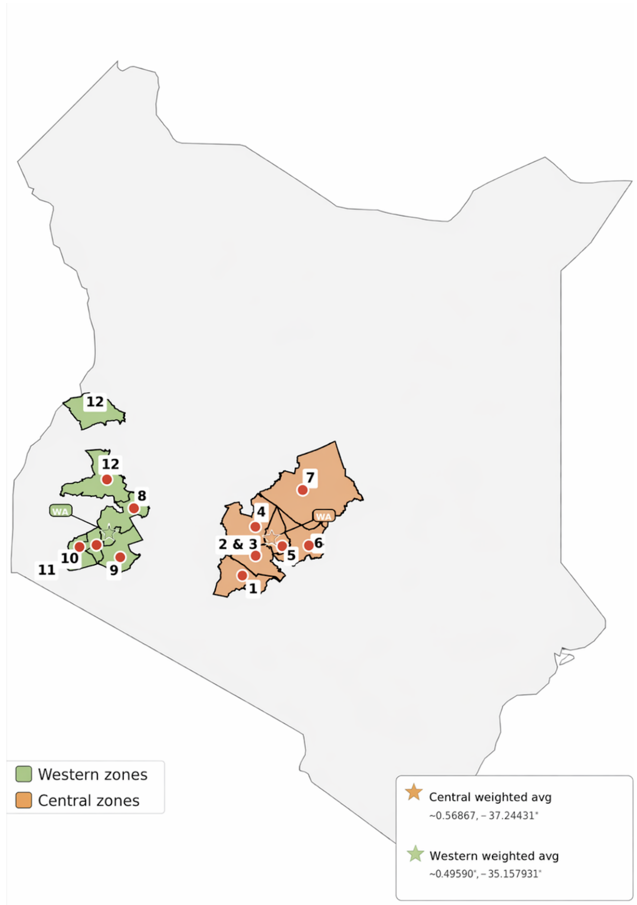


Figure 9: Map of zones where the case factories are located in Kenya.

Breakdown by factory size

Since the production volumes differ between the 70 case factories, with annual output of finished tea ranging from about 1,415,000 kg to 7,635,000 kg, they were further categorized into three groups: small, medium and large. The three sizes were decided by using z-score standardization, which is a statistical method assuming that the data is normally distributed. This method was chosen based on a recommendation from the KTDA Power Manager [I7]. The z-score measures how many standard deviations a data point deviates from the mean, as shown in Equation 7. Based on the selected z-score, the lower and upper cut-off values for the size categories were then calculated using Equation 8.

$$z = \frac{x - \mu}{\sigma} \tag{7}$$

$$\begin{aligned} X_{\text{lower}} &= \mu - z \cdot \sigma \\ X_{\text{upper}} &= \mu + z \cdot \sigma \end{aligned} \tag{8}$$

where
x = Observed data point
μ = Mean value
z = Z-score
σ = Standard deviation

Equation 8 were used with a selected z-score of 0.431. After the cut-off values $X_{\text{lower}}, X_{\text{upper}}$ were determined, all 70 factories could be divided into each size category based on their production volumes. The number of factories in each category and region is presented in Table 5 below.

Table 5: Classification of tea factories by size and regional distribution

Size	**Annual output (kg made tea)**	**Number of factories**	
		West	**Central**
Small	< 3,860,677	12	9
Medium	3,860,677–4,939,138	7	18
Large	> 4,939,138	14	10

As mentioned in section 1.4, only the medium-sized factories has been considered for this report. The reason for this delimitation was to account for the limited project time frame and to ensure the scope and results are easily interpretable.

Current energy setup

As previously mentioned, Kenyan tea factories rely on both thermal and electric energy, where electricity accounts for approximately 9–15 % [4], [5]. However, the electricity demand remains high, driven by specific sections of the factories. During a site visit to Factory 1, energy audit data were collected to clarify energy consumption patterns in Cutting, Tearing and Curling (CTC) tea factories in Kenya. The share of electricity consumed by each section is presented in Figure 10.

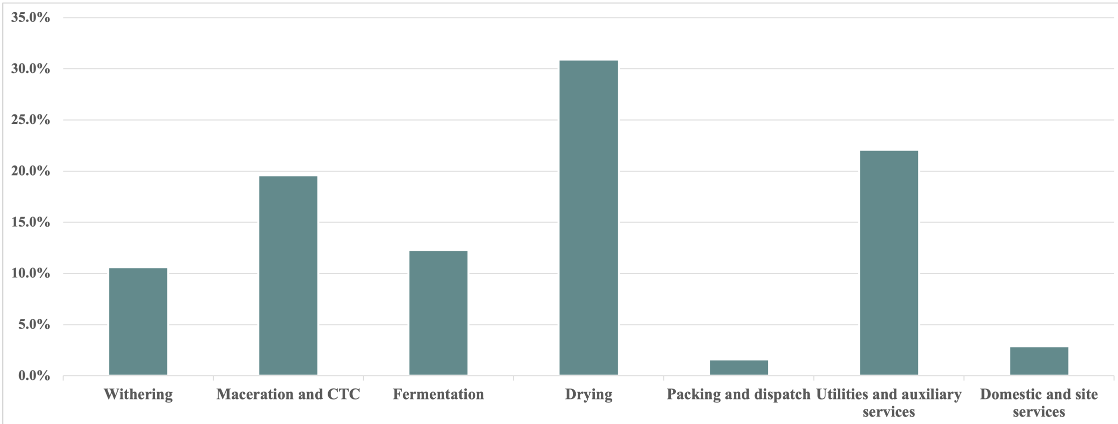


Figure 10: Share of total monthly electricity consumption by process step in the CTC tea manufacturing process in Factory 1.

The sections in the graph include the following equipment/loads:

- **Withering:** This process step consumes 10.6% of the total power. This is mainly due to fans with motors that require a lot of electricity to blow hot air and steam.
- **Maceration and CTC:** 19.6% of the total power consumed in a factory is required for the CTC roller motors and rotorvanes.
- **Fermentation:** Fermentation accounts for 12.3% of the total power which mainly is used for its conveyor belt motors.
- **Drying:** Drying accounts for 30.9% of the total used electricity. Force Drought (FD) fans consumes the most power to blow pressure through the radiators where steam passes through to create dry pressurised air as an output. Cyclon motors for recovering carry-on dust and tea particles also consumes a lot of power in this step.
- **Packing and dispatch:** Includes power for packing machines and lights which accounts for a total share of 1.6 %.
- **Utilities and auxiliary services:** This section consumes the second most power, 22.1%, and includes the rest of the loads, for example, office lights and and kitchen appliances.
- **Domestic and site services:** This section refers to power mainly used for employee residence and security lights, which is 2.9% of the total power consumed in the factory.

Electricity prices

National grid – Kenya Power and Lighting Company (KPLC). Data on the unit cost of electricity for all case factories were collected during all months in 2024. The average paid price for a used kWh for all factories in each zone is presented in Table 6.

Table 6: Average unit cost of electricity by region and zone

Region	Central							West				
Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Average unit cost of electricity (USD/kWh)	0.217	0.213	0.192	0.195	0.213	0.208	0.219	0.201	0.202	0.210	0.226	0.209

The electricity was purchased from the national grid in Kenya, KPLC. The average electricity price per kWh in 2024 was 0.208 USD/kWh for the central region and 0.210 USD/kWh for the west. Since the calculated average prices were similar, the price per kWh was rounded to 0.210 USD for all studied factories. Given that this was the total price per kWh paid by the case factories' grid electricity consumption, it includes both fixed and variable fees, such as transmission and connection fees.

Electricity tariffs in Kenya are relatively high, with a national average of 0.220 USD/kWh in 2025. This places the country third highest is Africa [46]. They rank among the 40 highest globally, mainly surpassed by nations that are highly dependent on imported fossil fuels (and thus sensitive to the political uncertainties and insecurities of the last few years) or with high taxes on tariffs, and their electricity prices stand out particularly when considering the country's economic context. For example, Kenya is placed just below Sweden (with a national average of 0.230 USD / kWh). However, the Gross National Product (GDP) per capita in Kenya is around 2132 USD, whilst Sweden's is more than 25 times greater at 57 118 USD [47]. This indicates that electricity costs place a significantly greater burden on Kenyan industries relative to their economic capacity. As previously discussed in this report, and as highlighted by the acting director at the Tea Board of Kenya during the interview [I6], high electricity prices represent a major challenge for Kenyan tea factories. Production costs are high relative to the value of the finished product on the global market, and the interviewee emphasized that reducing these costs is one of the most important steps to strengthen the sector's sustainability and global competitiveness. Since electricity constitutes a significant share of total production costs, it represents a key area for potential improvement. Given the high national electricity prices, adopting alternative and cheaper energy sources stands out as a clear and relevant pathway for tea factories to respond to this.

The number 0.210 USD/kWh differs slightly from the 2025 national average, but since it is calculated based on provided historic data on the specific case factories, it is considered more applicable for the calculations in this report. Moreover, the average electricity tariff often differs between industrial and residential consumers [48], also supporting the use of the calculated tariff rather than the national average.

Backup generator

While power from KPLC is the primary electricity source in tea factories, contributing to around 98% of the electricity mix, generators contribute with a small share of about 2%. Since the generator's fuel is diesel, the average diesel consumption for all factories was collected during all months in 2024 to do a better cost estimation. The annual average consumption for all factories is presented in Table 7.

Table 7: Average annual diesel consumption in liters by region and size-category

Diesel consumption (liter/year)			
Zone	Small	Medium	Large
1	30897.50	20088.86	23631.42
2	20823.00	23147.04	26759.00
3	-	9872.58	-
4	9089.48	6730.79	-
5	-	11872.35	12098.87
6	7723.38	28433.62	26339.00
7	23619.30	30901.48	24941.37
Avg Central	18430.53	18720.96	22753.93
8	-	25077.63	18838.80
9	-	12359.00	21830.45
10	23024.33	18921.70	34574.00
11	17110.83	-	-
12	13171.77	6145.00	-
Avg West	17768.98	15625.83	25081.08

Based on the diesel volumes presented in the previous table and an average diesel price of 1.317 USD per liter, the total annual electricity cost associated with backup generator use could be determined. In addition, the average electricity price per kWh could be calculated using an assumed conversion rate of 3.0 kWh per liter of diesel [5]. The estimated value for the average diesel price used in this study was set on the basis of the numbers used by both Miale Solar and KTDA, as identified from collected data.

Net Metering

Net Metering is a system in which consumers with on-site renewable energy systems can sell their surplus electricity to the grid. This means that the peak load demand at a given time has been fulfilled while the system continues to generate power. Net Metering is relevant for Kenyan tea factories that consider installing PV systems since the factories' load profiles are not ideally aligned with the solar PV production patterns. KTDA Power Manager explained that tea factories have high electricity demand during the night, although some flexibility may exist in withering and morning operations [I3]. The Production Manager at Factory 3 also stated that around 90% run at night, partly due to lower tariffs than during the day [I5].

Kenya's Net Metering framework is governed by the Energy (Net Metering) Regulations of 2025, adopted by the Energy and Petroleum Regulatory Authority (EPRA). The regulations indicate that all stakeholders are required to conduct a feasibility study report before any Net Metering project can be approved. The content of the report is highlighted under the Second Schedule of the regulations, and should cover grid impact assessments, protection schemes as well as environmental considerations. According to KTDA Power Manager [I3], qualified projects are also limited to 1 MW, and the size of the power system must be scaled according to the consumer's peak load. The interviewee explains that a facility with a 300 kW peak load are not allowed to install a 500 kW power system solely for exporting and selling excess electricity to the grid. Despite this legislative foundation, no projects are yet operating under the framework, with KPLC expected to lead in setting the practical rules for participation [I15].

Even though Net Metering for solar PV systems is not yet implemented, Strathmore University in Nairobi has secured a Feed-in-Tariff PPA with KPLC under the 2012 regulations and registered as an Independent Power Producer. Their system was installed in June 2014 and has a capacity of 600 kilowatt peak (kWp) with 2,400 PV modules and 25 inverters across the roofs of six buildings on campus [I15]. The system generates about 2 MWh per day during operation. Approximately 80% of the generated power is consumed by the load, while the remaining 20% is exported and sold to the grid. The exported electricity is sold at 0.12 USD/kWh, while imported and exported electricity are metered separately. As a result, an engineer at Strathmore [I15] explains that the university saves about 30% on its annual electricity bill from KPLC. However, it is also explained that the project's on-site consumption is more financially beneficial than exporting electricity to the grid. Compared with the export tariff of 0.12 USD/kWh, they have a grid tariff of about 0.17 USD/kWh. If the Net Metering regulations were implemented in the future, exported surplus electricity would receive a 50% credit, making it even less profitable than direct self-consumption. On the other hand, more costs are saved than in the current scenario for many solar PV systems, where the generated excess electricity is cut off instead of being utilized. Overall, the Strathmore project shows that installed solar PV systems can significantly reduce electricity costs for large C&I consumers in Kenya.

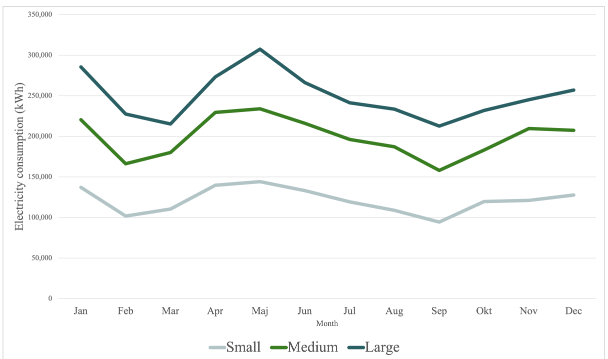
The main problem with the Net Metering system in Kenya is not the lack of regulation, but the gap between legislation and reality. The laws are there, but action is not being taken due to a lack of knowledge and bureaucracy. According to Miale's CFO [I10], Net Metering would be a game changer for the industry, but the actual implementation of the system has taken years and is yet to be active. It is also mentioned that most existing grid-tied PV systems are already compatible with implementing Net Metering, and that the only step missing from a technical standpoint is a new meter. The CEO at Miale [I9] also explains that without the possibility to export excess electricity, the developers of solar systems must size their systems with limited capacity since any generation above on-site demand is curtailed. To understand the scale of this, the CFO points out that Kenya's specific solar yield of around 1,500 kWh/kWp is 30% more than the average industrial consumption of about 1,000 kWh/kWp. This means that roughly 30% of the capacity may currently be lost.

There are still some factors that need to be taken into consideration before implementation. In an interview with the Technical Advisor to the Cabinet Secretary at the Ministry of Energy and Petroleum [I14], it was acknowledged that Net Metering works well in large and stable grids, but concerns about Kenya's relatively small electricity load of about 3 GW were raised. From this perspective, it could be a risk to scale a Net Metering system to export surplus electricity across the country. It could create a risk of over-generation at the system level. This concern may explain EPRA's cautious approach, requiring feasibility study reports before approval, and why the implementation of a Net Metering system has been postponed for many years.

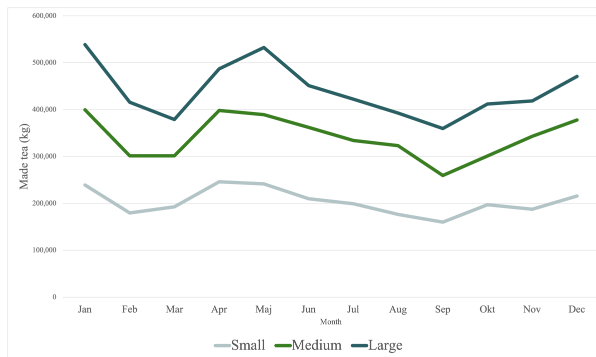
Load profile

Monthly average

Based on the energy data obtained from 70 KTDA-managed factories, average monthly load profiles were established for small, medium, and large factories in both regions. The average monthly data in 2023 and 2024, for Region West is plotted in Figure 11a and in Figure 12a for Cental. Figure 11b and 12b plot the average output of made tea during the same period in each region.



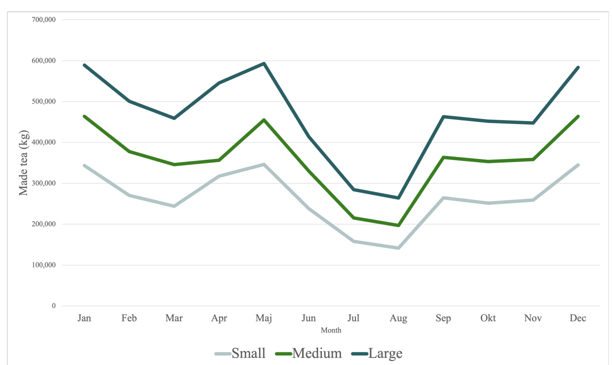
(a) Average monthly electricity consumption



(b) Average monthly kilograms of made tea

Figure 11: Annual pattern of electricity consumption and kilograms output of made tea in Region West in 2023/2024.

(a) Average monthly electricity consumption



(b) Average monthly kilograms of made tea

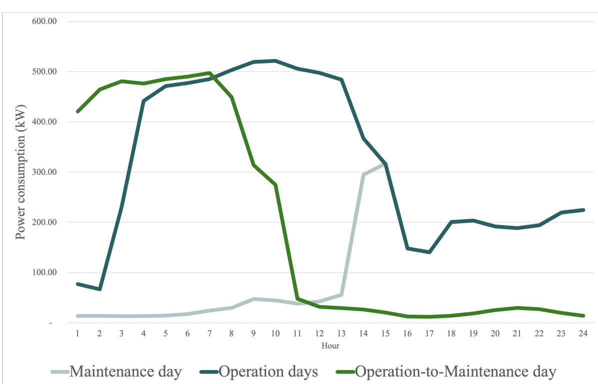
Figure 12: Annual pattern of electricity consumption and kilograms output of made tea in Region Central in 2023/2024.

By analysing both plots, a conclusion can be drawn that the load profile for factories in both regions correlates with their production volumes. However, the patterns for load profile and output tea differ slightly between the regions. It is shown that the plotted curves in Figure 11 do not vary as much as in Figure 12, indicating a more stable production and energy consumption pattern.

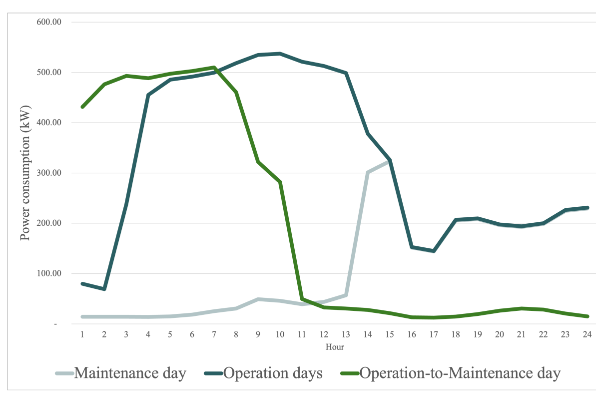
These changes in both production and energy demand can be caused by several different factors. According to interviewees [I5], [I6], [I2], and [I1], weather conditions were pointed out as an important explanation for changes in production and thus power consumption. [I5] explained that during the rainy season, the incoming green leaf is wetter, which makes withering take longer. In contrast, the factory can rely more on natural drying and needs much less steam during the dry season. [I6] similarly emphasized that climate change has made rainfall increasingly unreliable, with both excessive and insufficient rain affecting tea production. At Factory 1, [I1] described how electricity and firewood use increase during peak crop periods and how rainy conditions raise firewood consumption because higher moisture lowers combustion efficiency. [I2] likewise noted that factories are often more productive during the dry season and that weather can affect both fuel conditions and factory operations.

Daily average

For the daily power consumption, calculations were made based on measured data from Miale Solar at Factory 1 during a site visit in February 2026. The obtained data logging from the factory included power data for every hour during five days of the week. According to [I11], [I7] and [I4], power consumption patterns are generally similar every week and are the following: the week starts with maintenance on Mondays, followed by regular operating days from Tuesday to Saturday, and Sunday is an operation-to-maintenance day. Based on this information, it was assumed that the measured hourly data could be combined with the monthly power consumption and weekly behaviors to get an accurate consumption rate for every hour in a year. Based on the estimated rate, the average daily load profile for a factory within the category medium could be determined for both regions. The load profile for an average day in 2023/2024 is plotted for Region West in Figure 13a and Region Central in Figure 13b.



(a) Average hourly power consumption of medium-scale tea factories in Region West



(b) Average hourly power consumption of medium-scale tea factories in Region Central

Figure 13: Daily average load profile for a medium-scale factory in both regions

The average daily load profile is similar for both regions because they are based on the same modeling data from Factory 1. The only difference is in the scale, with Region Central showing slightly higher power consumption.

5.2. PV energy performance

Technically feasible solar PV systems

Based on Deldens's simulation procedure, described in section 3.3, data on technically feasible and optimized solar power systems for the case factories were obtained.

Through sensitivity analyses, Delden identified the optimal tilt angle and orientation of the system to maximize the total energy used for solar PV systems in both Region West and Region Central.

- **Scenarios without BESS**
  For Region West, it was found that the optimal tilt angle for the panels was 30° with an azimuth angle of 90°, corresponding to an east-facing orientation. For Region Central, the optimal panel tilt angle was found to be 15° with an azimuth angle of 135°, indicating a south-east-facing orientation [43].
- **Scenarios with BESS**
  For the scenarios including BESS, the optimal tilt and azimuth angle differ slightly from the previous scenario. For Region West, the optimal tilt angle for the panels was found to be 20° with an azimuth angle of 90°, corresponding to an east-facing orientation. For Region Central, the optimal tilt angle was 10° with an azimuth angle of 225°, indicating a south-west-facing orientation [43].

Using this as a basis, Delden identified eight technically feasible PV systems without BESS and sixty-four with BESS for each region. These systems were determined by scaling the system size in relation to the peak load (99%). The scaling ranged between 0.25 and 2.00.

The results obtained from Deldens study for the scenario without BESS are presented in Table 8.

Table 8: Simulated technically feasible PV systems without BESS for both regions [43]

(a) Region West

Scaling	DC Capacity (kW)	AC Capacity (kW)	No. of strings	No. of inverters	Tot energy produced (kWh)	Tot energy used (kWh)	Curt. (%)
0.25	184.8	150	21	5	285,066	246,225	13.6
0.5	360.8	300	41	10	557,386	461,319	17.2
0.75	536.8	450	61	15	829,471	661,494	20.3
1	712.8	600	81	20	1,101,517	801,232	27.3
1.25	888.8	750	101	25	1,373,552	872,811	36.5
1.5	1,064.8	900	121	30	1,645,581	916,833	44.3
1.75	1,240.8	1,020	141	34	1,915,817	949,075	50.5
2	1,425.6	1,170	162	39	2,200,926	975,058	55.7

(b) Region Central

Scaling	DC Capacity (kW)	AC Capacity (kW)	No. of strings	No. of inverters	Tot energy produced (kWh)	Tot energy used (kWh)	Curt. (%)
0.25	202.4	180	23	6	310,421	268,002	13.7
0.5	404.8	330	46	11	618,546	500,207	19.1
0.75	607.2	510	69	17	930,020	684,248	26.4
1	800.8	660	91	22	1,224,843	798,578	34.8
1.25	1,003.2	840	114	28	1,536,262	870,802	43.3
1.5	1,205.6	990	137	33	1,843,412	918,323	50.2
1.75	1,408.0	1,170	160	39	2,154,991	953,486	55.8
2	1,601.6	1,320	182	44	2,449,687	980,425	60.0

For the BESS scenario, Delden's analysis resulted in 64 different solar power systems. The systems have different combinations of PV modules and battery units, but are all technically feasible. Based on these results, assumptions were made to reduce the number of systems before continuing with the financial analysis. These assumptions were based on the maximum number of battery units that each PV system size can utilize. For example, smaller PV systems with fewer modules cannot produce enough excess power to fully utilize many battery units, since the battery capacity exceeds the available PV capacity. These system combinations were therefore excluded. The selected and sorted results obtained from Delden are presented in Table 9 for Region West and Table 10 for Region Central.

Table 9: Selected technically feasible PV systems with BESS for Region West [43]

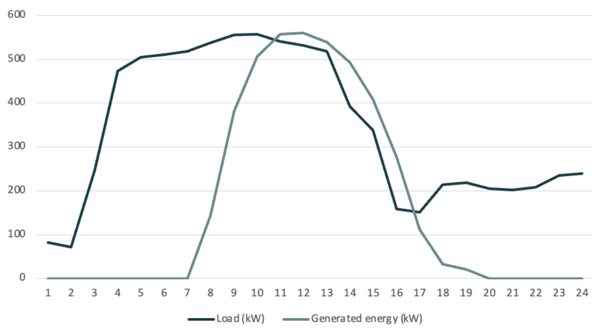
Battery units	Scaling	No. Of strings	No. Of inverters	DC Capacity (kW)	AC Capacity (kW)	Tot energy used (kWh)	Curt (%)	Battery units	Scaling	No. Of strings	No. Of inverters	DC Capacity (kW)	AC Capacity (kW)	Tot energy used (kWh)	Curt (%)
1	0.25	21	5	184.8	150	269937	5.7	3	1.5	121	30	1064.8	900	1117814	31.5
1	0.5	41	10	360.8	300	488833	12.9	3	1.75	141	34	1240.8	1020	1163174	38.8
1	0.75	61	15	536.8	450	696410	16.6	3	2	162	39	1425.6	1170	1195575	45.2
1	1	81	20	712.8	600	855977	22.6	4	1	81	20	712.8	600	928342	15.4
1	1.25	101	25	888.8	750	945110	31.4	4	1.25	101	25	888.8	750	1080205	20.6
1	1.5	121	30	1064.8	900	994457	39.7	4	1.5	121	30	1064.8	900	1168711	28.1
1	1.75	141	34	1240.8	1020	1030375	46.4	4	1.75	141	34	1240.8	1020	1222230	35.4
1	2	162	39	1425.6	1170	1059226	52.0	4	2	162	39	1425.6	1170	1258493	42.1
2	0.5	41	10	360.8	300	502323	10.3	6	1.25	101	25	888.8	750	1131006	16.6
2	0.75	61	15	536.8	450	711218	14.6	6	1.5	121	30	1064.8	900	1254701	22.4
2	1	81	20	712.8	600	890806	19.1	6	1.75	141	34	1240.8	1020	1327566	29.4
2	1.25	101	25	888.8	750	1001544	26.9	6	2	162	39	1425.6	1170	1376845	36.2
2	1.5	121	30	1064.8	900	1061023	35.3	8	1.5	121	30	1064.8	900	1318798	18.2
2	1.75	141	34	1240.8	1020	1099918	42.4	8	1.75	141	34	1240.8	1020	1419629	24.1
2	2	162	39	1425.6	1170	1130301	48.5	8	2	162	39	1425.6	1170	1482773	31.0
3	0.75	61	15	536.8	450	722095	13.2	10	1.5	121	30	1064.8	900	1360841	15.4
3	1	81	20	712.8	600	913034	16.9	10	1.75	141	34	1240.8	1020	1494144	19.9
3	1.25	101	25	888.8	750	1044586	23.5	10	2	162	39	1425.6	1170	1579533	26.2

Table 10: Selected technically feasible PV systems with BESS for Region Central [43]

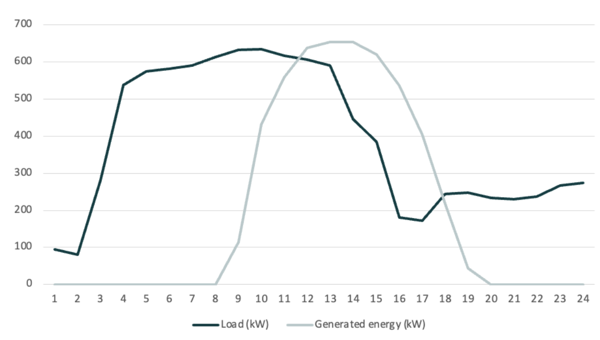
Battery units	Scaling	No. Of strings	No. Of inverters	DC Capacity (kW)	AC Capacity (kW)	Tot energy used (kWh)	Curt (%)	Battery units	Scaling	No. Of strings	No. Of inverters	DC Capacity (kW)	AC Capacity (kW)	Tot energy used (kWh)	Curt (%)
1	0.25	23	6	202.4	180	296826	7.0	3	1.75	160	39	1408.0	1170	1144863	47.7
1	0.5	46	11	404.8	330	547149	13.8	3	2	182	44	1601.6	1320	1174679	52.8
1	0.75	69	17	607.2	510	733478	23.1	4	1	91	22	800.8	660	987114	20.3
1	1	91	22	800.8	660	849779	32.3	4	1.25	114	28	1003.2	840	1094063	29.5
1	1.25	114	28	1003.2	840	926635	41.2	4	1.5	137	33	1205.6	990	1159344	37.8
1	1.5	137	33	1205.6	990	979560	48.2	4	1.75	160	39	1408.0	1170	1204414	44.7
1	1.75	160	39	1408.0	1170	1017845	54.0	4	2	182	44	1601.6	1320	1235621	50.1
1	2	182	44	1601.6	1320	1045985	58.4	6	1	91	22	800.8	660	1040280	15.7
2	0.5	46	11	404.8	330	562983	11.0	6	1.25	114	28	1003.2	840	1180494	23.5
2	0.75	69	17	607.2	510	774397	18.4	6	1.5	137	33	1205.6	990	1263708	31.7
2	1	91	22	800.8	660	905646	27.5	6	1.75	160	39	1408.0	1170	1317490	39.1
2	1.25	114	28	1003.2	840	988516	36.9	6	2	182	44	1601.6	1320	1353275	45.0
2	1.5	137	33	1205.6	990	1044037	44.5	8	1.25	114	28	1003.2	840	1247339	18.9
2	1.75	160	39	1408.0	1170	1083901	50.7	8	1.5	137	33	1205.6	990	1356589	26.3
2	2	182	44	1601.6	1320	1112676	55.5	8	1.75	160	39	1408.0	1170	1422043	33.9
3	0.75	69	17	607.2	510	800058	15.4	8	2	182	44	1601.6	1320	1465520	40.1
3	1	91	22	800.8	660	951273	23.5	10	1.5	137	33	1205.6	990	1432666	21.9
3	1.25	114	28	1003.2	840	1043249	33.1	10	1.75	160	39	1408.0	1170	1518935	29.1
3	1.5	137	33	1205.6	990	1103091	41.0	10	2	182	44	1601.6	1320	1570669	35.4

Solar resource and PV generation potential

To better understand the solar PV production potential in Region Central and West, solar generation and the daily load profile was plotted for both regions. This enabled an analysis of how the hourly solar resource pattern relates to the average factory consumption behavior over 24 hours.



(a) Region West



(b) Region Central

Figure 14: Average daily solar energy generation [kW] profiles for the best case systems (scale 1.0) in both regions compared with representative medium factory load profiles [kW] [43].

The profiles in Figure 14 are plotted only for the peak-load scale and over the first 24 hours, so some variation may occur over the year. Plotting for a larger scaled system would move the peak of the generation curve higher, and a smaller system would be lower, but it would still stretch across the same hours. Plotting consumption and generation together provides a useful indication of how the timing of the available solar resource corresponds to the timing of electricity demand in the factories. By looking at the available solar energy in both Figure 14a and 14b, it is shown that it matches the electricity demand relatively well. However, the demand peaks earlier in the day and remains high also in the late afternoon. When comparing the potential between the regions, the solar generation for Region West matches the electricity load slightly better compared to Region Central, since it's higher in the morning and peaks earlier in the day.

Overall, the figure shows that one of the main technical challenges is the timing of the solar irradiation in relation to tea factory operations. The strongest solar resource is concentrated around noon, while electricity demand is distributed over a wider part of the day and differs between operation, maintenance, and transition days. This limits the direct use of generated PV electricity and supports the relevance of flexibility measures such as battery storage or export of surplus electricity through Net Metering.

5.3. Identified barriers and incentives

Technical factors

Several technical factors influence the feasibility of solar PV systems in Kenyan tea manufacturing, particularly related to system integration, reliability, and technology maturity.

A key technical constraint is the dependence of grid-tied solar systems on the availability of the national grid. Solar PV systems that are connected directly to the grid require a stable grid connection to function, as power outages directly affect system performance. In areas where flickering or grid interruptions occur, this directly reduces the utilization of installed solar capacity. To mitigate this issue, hybrid systems combining grid-tied solar PV with battery storage are often considered. However, interviewees [I7] and [I9] highlighted that battery storage introduces additional complexity and cost, and the technology is still perceived as relatively immature in the Kenyan context. There are cases where systems have not performed as expected due to insufficient technical knowledge or poor system design, indicating that not only the technology itself but also the availability of technical expertise is a critical factor [I10].

Another technical barrier is the intermittent nature of solar energy. As mentioned by the CEO of Miale Solar [I9], grid-tied olar PV cannot provide a stable and continuous energy supply without complementary systems, such as batteries or backup generators, both because of the inconsistent energy generation and because it will shut down when there are power outages or disturbances on the grid. This is particularly problematic in tea manufacturing, where processes are continuous and highly sensitive to interruptions [I1]. As a result, solar PV systems cannot function as standalone solutions and must be integrated with other energy sources [I14]. Additionally, technical constraints related to site conditions can limit implementation. Factors such as insufficient roof space, weak structural integrity, or lack of available land can make installation infeasible or significantly increase costs [I7]. These physical constraints directly affect system sizing and potential energy generation.

At the same time, technical incentives are supporting the transition to solar energy. PV systems are generally associated with low operational complexity and limited mechanical failure, which can reduce maintenance requirements and improve electricity reliability [I8]. Overall, the technical feasibility of solar PV in the tea industry is highly dependent on system design and integration. While the solar PV technology itself is mature and has technical benefits compared to other energy sources, challenges related to intermittency, grid dependence, and local technical capacity remain key barriers to implementation.

Operational factors

The operational characteristics of tea manufacturing play a central role in determining the feasibility of integrating solar PV systems at the factories.

The already discussed reliability issue functions as an operational barrier as well. As mentioned, tea factories operate as continuous processing plants, where interruptions in energy supply can directly affect product quality and lead to production losses. Because of this, factories rely heavily on stable and reliable energy sources, which limits the extent to which intermittent energy sources such as solar PV can be used in core production processes. Energy demand within tea factories is unevenly distributed across process stages. The drying stage is the most energy-intensive, followed by processes such as withering, cutting, and fermentation. These processes often require consistent and high energy input, limiting the extent to which intermittent solar energy can substitute grid electricity without additional battery storage or backup systems [I8].

Another operational barrier is the daily load profile of tea manufacturing. The load curve in tea factories is unfortunately very different from the generation curve of solar PV, with the main consumption occurring at night and early mornings. The misalignment between solar generation and energy demand affects overall utilization. At interviews with stakeholders in the tea sector, it was concluded that the production process cannot to any substantial extent be modified or re-scheduled to better align with solar generation, as the tea manufacturing is dependent on a whole ecosystem of process steps, beginning already at the tea farms, and proper treatment of the tea leaves is highly time sensitive [I1], [I2], [I3], [I4], [I5], [I6]. Due to this operational barrier, a solar PV system scaled after a tea factory's peak load would therefore have very low levels of utilization unless complemented with battery storage.

Economic factors

Economic considerations are the primary drivers influencing the adoption of solar PV systems in the tea industry. The main incentive for factories to invest in solar energy, highlighted in multiple interviews both with stakeholders in the tea industry ([I1], [I2], [I3], [I4], [I5], [I6]) and with representatives from Miale Solar ([I8], [I9], [I10], [I11], [I12]) is the potential for cost reduction in electricity expenses.

Solar PV systems offer the possibility of reducing reliance on grid electricity, which can lead to significant operational savings over time. The tariffs for electricity from the national grid, KPLC, are relatively high and account for a large share of the production costs in the tea sector [6], making cost savings from solar PV especially attractive. However, high upfront investment costs of the energy systems and additional battery storage solutions remain a major barrier. The capital expenditure can be significant, which limits adoption, especially for factories with constrained financial resources or competing investment priorities. When asked why solar PV had not been previously implemented, the interviewee at case factory 1 answered that there had been other more urgent investments in earlier years, restricting the funding possibility for a new solar energy system [I1]. Different financing models, such as Power Purchase Agreements (PPAs), leasing arrangements, and outright purchases, influence the feasibility for the user. While outright purchases can offer higher long-term returns, they require substantial upfront capital. In contrast, PPAs and leasing models reduce initial investment but may result in lower overall profitability [I12]. The availability and structure of financing solutions therefore play a critical role in enabling or constraining implementation.

Another economic barrier is the uncertainty regarding returns on investment. If the expected savings from solar PV are not significant enough, companies may choose not to proceed with installation [I7]. This is particularly relevant in cases where system utilization is limited due to operational or technical constraints, as discussed earlier in this chapter. There are also indirect economic risks linked to governance and decision-making structures within the tea sector. In some cases, investment decisions may be influenced by stakeholder perceptions, such as concerns that funds are being diverted from farmer payments to infrastructure projects. This can create resistance to large capital investments, including solar PV systems [I10]. With KTDA, the factory owners, i.e., the farmers, are the final decision makers, making awareness and perception a potential barrier for investments [I3]. At the same time, solar PV provides long-term economic incentives beyond direct cost savings. These include reduced exposure to rising energy prices, lower operational risks associated with fuel supply, and potential access to emerging revenue streams such as Net Metering and carbon credits [I14].

Regulatory factors and policies

Beyond the technical and operational factors, the feasibility of PV systems in Kenyan tea manufacturing is influenced by an evolving policy and regulatory framework that both enables and constrains adoption. As already mentioned, economic factors are highly prioritized when considering transitioning to solar energy, and there are indirect economic incentives related to the evolving frameworks.

One central regulatory development is the establishment of a formal framework on Net Metering, allowing consumers to generate electricity for self-consumption while remaining connected to the grid, as discussed in section 5.1.4. Under this system, Commercial and Industrial (C&I) consumers, e.g., tea factories, can install grid-tied solar energy systems for their own consumption, where excess electricity can be exported to the grid in exchange for energy credits. This is an important step toward enabling decentralized renewable energy adoption in the industrial sector. Especially in the tea industry, where under-utilization is a common occurrence (as discussed in section 5.2), the opportunity to sell the curtailment creates a strong economic incentive to implement solar PV [I3]. However, several regulatory constraints limit the economic attractiveness of larger-scale PV installations. First, system capacity is capped at 1 MW for C&I users and constrained by the users' contracted load. In addition, the total national capacity allocated to Net Metered systems is limited in this initial phase [49]. As mentioned, the total national load in Kenya, including both industries and residential consumption, amounts to about 3 GW. If all industries were to start feeding energy back into the grid to such a small utility, it would result in an imbalance between energy generation and consumption [I14]. Furthermore, exported electricity is credited at only 50% of the exported energy, meaning that the economic value of exported electricity is significantly lower than that of self-consumed electricity. Lastly, installation of Net Metered systems requires a formal agreement with the electricity licensee, and projects above a certain size must undergo feasibility studies conducted by licensed engineers [49]. As mentioned by [I7], the bureaucracy surrounding the approval processes, compliance with grid codes, and technical standards contributes to increased complexity, which can affect both the timeline and financial viability of solar PV projects.

Looking beyond Net Metering, broader policy developments also influence the feasibility of solar PV within the tea industry. Kenya has made significant progress in establishing a regulatory framework for carbon markets, particularly following amendments to the Climate Change Act and the development of supporting regulations [I18]. The carbon markets system is still under development, with ongoing regulatory uncertainty, but the current direction shows that carbon credits may provide an additional revenue stream for renewable energy projects and can thus create another economic incentive for investing in solar PV.

In addition to these direct policy developments, Kenya's broader energy strategy, as discussed in section 2.2.2, further shapes the feasibility of solar PV in industrial applications. The Least Cost Power Development Plan (LCPDP) 2024-2043 and the Ministry of Energy and Petroleum emphasize Kenya's plans to expand renewable energy while maintaining grid stability through sufficient baseload generation and investments in transmission and storage infrastructure [9], [I14]. This reflects a strategic approach where intermittent sources such as solar are encouraged, but carefully integrated to avoid destabilizing the grid. As highlighted in interviews, tea factories remain dependent on continuous and reliable energy supply due to the nature of their operations, which limits the extent to which solar PV can replace grid electricity in core processes [I14]. Moreover, the Ministry of Energy and Petroleum has made it mandatory for industrial actors on the Kenyan market to conduct proper energy audits. An interviewee at the United Nations Industrial Development Organization (UNIDO) [I16], involved in the Energy Efficiency for Sustainable Livelihoods in Africa (EELA) program, mentions this regulation as a step in the direction towards a more energy-efficient and renewable tea sector.

Overall, the current regulatory and policy environment in Kenya creates a mixed incentive structure for solar PV adoption in tea manufacturing. While frameworks such as Net Metering and emerging carbon markets provide economic incentives and signal long-term governmental support for renewable energy, there are regulatory constraints, grid limitations, and administrative requirements that act as a barrier towards large-scale deployment. Therefore, solar PV systems are currently primarily feasible as a complementary solution focused on self-consumption and cost reduction, rather than as a standalone energy source or significant revenue-generating asset.

5.4. Scenarios for comparison

From the qualitatively identified barriers and incentives, it is indicated that economic factors and cost-saving incentives are among the most important for stakeholders in the tea industry to consider transitioning to solar PV. In order to either deter or confirm this indication and best reply to the research question on the financial feasibility, the acquired qualitative data were used to make a scenario analysis on possible cost savings, as described in sections 3.3 and 4.2.3. Four scenarios were chosen based on both desire and likelihood of occurrence, concluded from interviews with stakeholders in both the tea sector, the energy sector, and the solar PV industry. As mentioned in 3.2.2, the main financial parameters used to compare the economic feasibility are the Levelized Cost of Energy (LCOE) for the PV system and the Average Electricity Price (AEP) for the energy system as a whole, both measured in USD/kWh and calculated using equations 1 and 2. The different scenarios include or exclude different features, which has an effect on the LCOE and AEP.

- **Base Case:** The base case is the scenario where no changes are made to the current energy system. For the cases used in this study, this means that all electricity is provided by the Kenyan national grid, KPLC, and the AEP is calculated as an average price per kWh based on previous electricity bills.
- **Grid-tied PV system, without Net Metering and Battery Energy Storage System (BESS):** As indicated by the name, this scenario considers a solar PV system without any battery storage and where Net Metering is assumed not possible. The AEP is thus calculated by applying the LCOE for the solar PV system and the cost of KPLC for the corresponding hours, depending on solar energy generation and consumption load. When the solar energy generation is higher than the load, it is assumed that the generation is simply cut off.
- **Grid-tied PV system, with Net Metering and without BESS:** As indicated by the name, this scenario considers a solar PV system without any battery storage but where Net Metering is assumed possible. Again, the AEP is calculated by applying the LCOE for the solar PV system and the cost of KPLC for the corresponding hours, depending on solar energy generation and consumption load. However, when the PV system generates more energy than the load, the excess energy has been considered a positive income, based on a fixed price per kWh as given by [I15].
- **Grid-tied PV system, with BESS and without Net Metering:** This scenario considers a solar PV system with battery storage. For this scenario, multiple sub-scenarios are considered including different sized batteries. When solar generated energy exceeds the load, the excess energy is used to charge a battery. When the PV system can no longer match the load, the battery is used first hand, before switching to the grid. AEP is calculated by applying the LCOE for the solar PV system as well as the cost of storage and the cost of discharge from the battery. During hours where the load exceeds solar generation or available stored energy, KPLC is used.

All scenarios include backup diesel use, but BESS scenarios assume diesel consumption is reduced to 10% of baseline based on suggestions by the CFO at Miale Solar. The simulation process, inputs and outputs are described in section 3.3 and section 4.3.5.

5.5. Input values

Depending on system size and scenario, input values to the MATLAB calculations varied. As did the simulated input data acquired through SAM. Calculations were made for each scenario and system size, and the input values varied as described below:

- **Scenario data:** Each scenario and system size was simulated in SAM. The simulation data included a column of the hourly load profile, as well as three columns containing the hourly split between solar generation energy, energy from the grid, and energy from solar to the grid (when applicable). These columns were used to ensure the correct cost figure was applied to the correct share of the load.

- **Grid - electricity price:** The price used for the energy provided by the national grid (KPLC) was 0.210 USD/kWh, as discussed in 5.1.4. This figure was assumed constant regardless of scenario, system size and hour.
- **Discounted electricity price:** To calculate the AEP and investment appraisal metrics for power purchasing agreements, a fixed discounted electricity price (as described in section 3.2.2.) was used instead of LCOE for the electricity generated by the solar PV system. After interviews with the CFO and Project Manager at Miale Solar ([I10], [I11]), this input was defined as 60% of the KPLC grid price. The MATLAB input was therefore 0.126 USD/kWh.
- **Net Metering - sell price:** The input price used for the energy sold back to the grid was 0.105 USD/kWh for the scenario where Net Metering was assumed possible. This is based on the assumption that sell price would be 50% of the grid price, as discussed in section 5.1.4.
- **Diesel - annual consumption:** The input value of the annual consumption of diesel (used for the backup generator) was, as described in section 5.1.4, calculated to approximately 18 721 litres/year for the central region and 15 626 litres/year for the west. For the scenario with a BESS, fuel savings would be significant, and the consumption would be assumed 10% of that for systems without storage. This consumption was simply added on top of the provided energy consumption. The reason for this is that diesel is consumed solely during power outages and interruptions on the national grid, which the simulation programs could not account for. Given that this applies to the entire analysis, including all scenarios and systems, it should not affect what conclusions are drawn from the results.
- **Diesel - price and energy conversion:** The diesel price used for the calculations was 1.3167 USD/litre and the energy conversion rate used is 3.0 kWh per litre of diesel. As mentioned in 5.1.4, these numbers were assumed based on discussions with both the Kenya Tea Development Association (KTDA) and Miale Solar.
- **Solar PV system size:** The solar PV system size input varied as displayed in Table 8a and 8b. The actual input is the DC capacity in the optimized systems simulated by Delden, which varies between 184.8-1425.6 kW for region West and 202.4-1601.6 kW for region Central.
- **Solar PV system Capital Expenses:** Both the CFO and Head of Procurement at Miale Solar mentioned during interviews ([I10], [I13]) that calculating the CapEx for a solar PV system requires case-specific design engineering knowledge and time-sensitive information on prices for each component. Due to the nature of this thesis, designing a full system with a complete bill of materials for the cases studied was not possible. Moreover, since the systems studied are purely hypothetical at this point, it is not possible to figure out exact prices on the hardware components, such as the inverters, PV cells, mounting gear and cables. After discussions with Miale Solar, it was decided to use estimated numbers for the CapEx of the system. The decided numbers vary depending on system size to take account for the economy of

scale, where three size intervals with different cost has been defined:

$$\text{System Size} < 200 \text{ kW} \implies \text{CapEx} = 500 \text{ USD / kW}$$

$$200 \text{ kW} < \text{System Size} < 500 \text{ kW} \implies \text{CapEx} = 450 \text{ USD / kW}$$

$$\text{System Size} > 500 \text{ kW} \implies \text{CapEx} = 400 \text{ USD / kW}$$

Which CapEx is used as input in MATLAB thus depends on which system is modeled. However, CapEx also depends on the investor perspective. As discussed in section 3.2, the different financing models opt for different stakeholders to take the cost of investment. The costs described here, 400, 450 or 500 USD/kW, represent the CapEx for the supplier in a PPA. With an outright purchase, the supplier would add a margin on the CapEx to ensure profitability on the affair, meaning that the customer's CapEx is higher. To take this into account, a profit margin of 30% is added when considering the consumer perspective of an outright purchase.

- **Solar PV system insurance, operations and maintenance:** Insurance cost as well as cost for Operations and Maintenance (O&M) are both dependent on the system size. For O&M, the cost is assumed to be 7.5 USD / kW. For insurance, cost is assumed to be 0.4% of total system CapEx. Both these inputs are based on information provided by Miale Solar during correspondence with the CFO.
- **Solar PV system lifetime, discount rate and degradation rate:** Based on information provided by Miale Solar, the PV system was assumed to have a life time of 25 years, a discount rate of 11% and a degradation rate of 0.5%.
- **BESS capacity, efficiency and cycles :** As introduced in section 2.3.3, the battery used has a capacity of 233 kWh per module. While peak efficiency is 95.5% [30], an average of 90% is used for the calculation to account for a more realistic system, given that most lithium-ion batteries have a round-trip efficiency of 87-94% [50]. Given that the energy system operates every day, the number of discharge cycles is 365 - one for each day of the year.
- **Number of modules:** Based on Delden's simulations, the number of battery modules used in the BESS varied between 1, 2, 3, 4, 6, 8, and 10. The system curtailment was taken into account when deciding on the maximum number of modules that were technically feasible for each system, and the number varied as displayed in Table 9 and 10.
- **BESS CapEx:** After discussion with the CFO of Miale Solar, it was decided that the storage CapEx should be 220 USD/kWh. To account for the whole BESS CapEx, this number is multiplied by the battery capacity and the number of modules installed. As with the PV cells, a 30% profit margin is added to calculate the consumer price.
- **BESS operations and maintenance:** The O&M cost of a BESS system is 5 USD/kWh, defined after discussion with Miale Solar.

- **BESS SOH:** The battery used for this study has a State of Health (SOH) requirement of 80% [30]. The simulation tool takes this into account. Since the lifetime of the PV system is 25 years, a re-investment of the BESS would be needed to account for the whole period if the BESS SOH gets below 80%. If this happens, the SAM simulation assumes a new battery is purchased, and the MATLAB code counts the BESS CapEx twice. However, in the case that the BESS SOH reaches below 80% in year 24, no extra CapEx is added since a re-investment at that point is not realistic.

5.6. Results

LCOE and AEP results

Through the simulation procedure, described in section 4.3.5, the Levelized Cost of Energy and the Average Electricity Price were determined for each scenario and each optimized solar power system presented in Table 8, Table 9 and Table 10 in section 5.2.1. LCOE was calculated using Equation 1, and used as input together with the grid price, diesel price and (for the scenario with Net Metering) export sell price to calculate AEP from Equation 2. All calculations were made considering both 1x CapEx and 1.3x CapEx, to ensure both the supplier perspective and consumer perspective are considered. For the power purchasing agreement (PPA) perspective, the fixed discounted electricity price (as described both in 3.2.2 and 5.5) was used to calculate AEP instead of $LCOE_{PV}$ and $LCOE_{battery}$. One exception is the Base Case scenario, for which no LCOE was calculated, since it assumes no solar PV system or BESS is installed. Instead, the full electricity consumption is assumed to be purchased from the national grid and via diesel. The AEP is still calculated using Equation 2, but assuming that the whole electricity load is included in (and therefore priced as) E_{grid}. The cost of energy consumption from diesel is added based on the annual consumption and the given cost of fuel, as explained in section 5.5.

While LCOE was calculated to understand and compare the cost of the energy system itself, AEP was used to evaluate the resulting electricity cost for each system for the factory as a whole, including the remaining dependence on KPLC electricity and backup diesel consumption. The resulting values were then used together to compare the cost-saving potential of the different scenarios and systems, and to determine under which conditions solar PV systems could be considered the most optimal for tea factories in Kenya from a financial perspective. The results from these simulations and calculations are presented in Table 11 for the base case scenario, Tables 12 and 13 for scenarios without BESS and in Tables 14 and 15 for the scenario including BESS.

Table 11: Base Case: *Annual load, diesel consumption and customer AEP*

Region	Load / year	Diesel consumption / year (L)	Grid price / kWh	Diesel price / kWh	AEP
West	2,387,725.86	15,625.83	0.2100	0.4389	0.2144
Central	2,457,722.92	18,720.96	0.2100	0.4389	0.2151

Table 12: Systems without BESS / Outright Purchase: *LCOE and customer AEP*

(a) System capex: 1x

Scale	DC cap (kW)	LCOE
Region: West		
0.25	184.8	0.0449
0.5	360.8	0.0409
0.75	536.8	0.0369
1	712.8	0.0369
1.25	888.8	0.0369
1.5	1064.8	0.0369
1.75	1240.8	0.0369
2	1425.6	0.0369
Region: Central		
0.25	202.4	0.0412
0.5	404.8	0.0413
0.75	607.2	0.0372
1	800.8	0.0372
1.25	1003.2	0.0372
1.5	1205.6	0.0373
1.75	1408.0	0.0372
2	1601.6	0.0372

(b) System capex: 1.3x

Scale	DC cap (kW)	LCOE	AEP No NM	AEP NM
Region: West				
0.25	184.8	0.0569	0.1993	0.1975
0.5	360.8	0.0516	0.1855	0.1808
0.75	536.8	0.0464	0.1736	0.1645
1	712.8	0.0464	0.1672	0.1516
1.25	888.8	0.0464	0.1668	0.1416
1.5	1064.8	0.0464	0.1686	0.1328
1.75	1240.8	0.0465	0.1714	0.1246
2	1425.6	0.0465	0.1749	0.1161
Region: Central				
0.25	202.4	0.0520	0.1983	0.1963
0.5	404.8	0.0522	0.1846	0.1789
0.75	607.2	0.0468	0.1739	0.1617
1	800.8	0.0469	0.1708	0.1497
1.25	1003.2	0.0468	0.1715	0.1390
1.5	1205.6	0.0469	0.1740	0.1294
1.75	1408.0	0.0469	0.1776	0.1201
2	1601.6	0.0469	0.1816	0.1116

Table 13: Systems without BESS / PPA: *LCOE and customer AEP*

Scale	DC Capacity (kW)	LCOE	PPA AEP
Region: West			
0.25	184.8	0.0449	0.2057
0.5	360.8	0.0409	0.1980
0.75	536.8	0.0369	0.1915
1	712.8	0.0369	0.1868
1.25	888.8	0.0369	0.1844
1.5	1064.8	0.0369	0.1829
1.75	1240.8	0.0369	0.1818
2	1425.6	0.0369	0.1809
Region: Central			
0.25	202.4	0.0412	0.2059
0.5	404.8	0.0413	0.1976
0.75	607.2	0.0372	0.1913
1	800.8	0.0372	0.1877
1.25	1003.2	0.0372	0.1854
1.5	1205.6	0.0373	0.1839
1.75	1408.0	0.0372	0.1828
2	1601.6	0.0372	0.1820

Table 14: Systems with BESS / Outright Purchase: *System LCOE and customer AEP*

Region: West

System setup			1x capex	1.3x capex		
Batt. units	**Scale**	**DC cap (kW)**	**Sys LCOE**	**Sys LCOE**	**AEP**	**Batt. repl.**
1	0.25	184.8	0.0802	0.1012	0.1953	0
1	0.50	360.8	0.0659	0.0831	0.1825	0
1	0.75	536.8	0.0598	0.0753	0.1702	1
1	1.00	712.8	0.0627	0.0790	0.1636	2
1	1.25	888.8	0.0680	0.0857	0.1616	2
1	1.50	1064.8	0.0746	0.0940	0.1623	2
1	1.75	1240.8	0.0817	0.1029	0.1641	2
1	2.00	1425.6	0.0895	0.1127	0.1669	2
2	0.50	360.8	0.0802	0.1009	0.1820	0
2	0.75	536.8	0.0706	0.0888	0.1696	1
2	1.00	712.8	0.0721	0.0909	0.1630	2
2	1.25	888.8	0.0759	0.0957	0.1612	2
2	1.50	1064.8	0.0818	0.1031	0.1617	2
2	1.75	1240.8	0.0878	0.1107	0.1632	2
2	2.00	1425.6	0.0953	0.1202	0.1661	2
3	0.75	536.8	0.0815	0.1025	0.1693	1
3	1.00	712.8	0.0789	0.0994	0.1620	1
3	1.25	888.8	0.0838	0.1057	0.1607	2
3	1.50	1064.8	0.0885	0.1117	0.1612	2
3	1.75	1240.8	0.0938	0.1184	0.1627	2
3	2.00	1425.6	0.1010	0.1274	0.1656	2
4	1.00	712.8	0.0880	0.1109	0.1616	1
4	1.25	888.8	0.0905	0.1142	0.1598	2
4	1.50	1064.8	0.0951	0.1201	0.1608	2
4	1.75	1240.8	0.0996	0.1257	0.1622	2
4	2.00	1425.6	0.1049	0.1324	0.1644	2
-	-	-	-	-	-	
6	1.25	888.8	0.1041	0.1313	0.1584	2
6	1.50	1064.8	0.1061	0.1340	0.1591	2
6	1.75	1240.8	0.1097	0.1386	0.1608	2
6	2.00	1425.6	0.1142	0.1442	0.1633	2
-	-	-	-	-	-	
8	1.50	1064.8	0.1159	0.1463	0.1572	2
8	1.75	1240.8	0.1176	0.1485	0.1587	2
8	2.00	1425.6	0.1220	0.1541	0.1616	2
10	1.50	1064.8	0.1258	0.1587	0.1555	2
10	1.75	1240.8	0.1245	0.1571	0.1563	2
10	2.00	1425.6	0.1277	0.1612	0.1591	2

Region: Central

System setup			1x capex	1.3x capex		
Batt. units	**Scale**	**DC cap (kW)**	**Sys LCOE**	**Sys LCOE**	**AEP**	**Batt. repl.**
1	0.25	202.4	0.0729	0.0918	0.1935	0
1	0.50	404.8	0.0665	0.0840	0.1811	1
1	0.75	607.2	0.0631	0.0795	0.1713	1
1	1.00	800.8	0.0689	0.0868	0.1678	2
1	1.25	1003.2	0.0760	0.0958	0.1671	2
1	1.50	1205.6	0.0837	0.1055	0.1683	2
1	1.75	1408.0	0.0920	0.1159	0.1707	2
1	2.00	1601.6	0.1005	0.1266	0.1740	2
2	0.50	404.8	0.0809	0.1020	0.1807	1
2	0.75	607.2	0.0727	0.0916	0.1705	1
2	1.00	800.8	0.0771	0.0973	0.1669	2
2	1.25	1003.2	0.0833	0.1050	0.1664	2
2	1.50	1205.6	0.0901	0.1136	0.1674	2
2	1.75	1408.0	0.0981	0.1237	0.1699	2
2	2.00	1601.6	0.1056	0.1331	0.1730	2
3	0.75	607.2	0.0828	0.1043	0.1699	1
3	1.00	800.8	0.0843	0.1063	0.1659	2
3	1.25	1003.2	0.0901	0.1137	0.1656	2
3	1.50	1205.6	0.0961	0.1212	0.1667	2
3	1.75	1408.0	0.1037	0.1308	0.1693	2
3	2.00	1601.6	0.1104	0.1393	0.1722	2
4	1.00	800.8	0.0922	0.1162	0.1652	2
4	1.25	1003.2	0.0955	0.1205	0.1645	2
4	1.50	1205.6	0.1016	0.1282	0.1659	2
4	1.75	1408.0	0.1076	0.1357	0.1681	2
4	2.00	1601.6	0.1150	0.1451	0.1715	2
6	1.00	800.8	0.1076	0.1357	0.1641	2
6	1.25	1003.2	0.1071	0.1351	0.1628	2
6	1.50	1205.6	0.1114	0.1407	0.1642	2
6	1.75	1408.0	0.1164	0.1469	0.1664	2
6	2.00	1601.6	0.1217	0.1535	0.1692	2
8	1.25	1003.2	0.1172	0.1478	0.1609	2
8	1.50	1205.6	0.1189	0.1501	0.1618	2
8	1.75	1408.0	0.1239	0.1564	0.1645	2
8	2.00	1601.6	0.1280	0.1616	0.1672	2
10	1.50	1205.6	0.1276	0.1611	0.1601	2
10	1.75	1408.0	0.1292	0.1631	0.1619	2
10	2.00	1601.6	0.1344	0.1697	0.1654	2

Table 15: Systems with BESS / PPA: *System LCOE and customer AEP*

Region: West

Batt. units	Scale	DC cap (kW)	Sys LCOE	AEP (USD/kWh)	Batt. repl.
1	0.25	184.8	0.0802	0.2022	0
1	0.50	360.8	0.0659	0.1951	0
1	0.75	536.8	0.0598	0.1888	1
1	1.00	712.8	0.0627	0.1848	2
1	1.25	888.8	0.0680	0.1825	2
1	1.50	1064.8	0.0746	0.1807	2
1	1.75	1240.8	0.0817	0.1794	2
1	2.00	1425.6	0.0895	0.1783	2
2	0.50	360.8	0.0802	0.1951	0
2	0.75	536.8	0.0706	0.1889	1
2	1.00	712.8	0.0721	0.1854	2
2	1.25	888.8	0.0759	0.1836	2
2	1.50	1064.8	0.0818	0.1821	2
2	1.75	1240.8	0.0878	0.1808	2
2	2.00	1425.6	0.0953	0.1799	2
3	0.75	536.8	0.0815	0.1889	1
3	1.00	712.8	0.0789	0.1852	1
3	1.25	888.8	0.0838	0.1844	2
3	1.50	1064.8	0.0885	0.1833	2
3	1.75	1240.8	0.0938	0.1821	2
3	2.00	1425.6	0.1010	0.1813	2
4	1.00	712.8	0.0880	0.1854	1
4	1.25	888.8	0.0905	0.1848	2
4	1.50	1064.8	0.0951	0.1844	2
4	1.75	1240.8	0.0996	0.1834	2
4	2.00	1425.6	0.1049	0.1823	2
-	-	-	-	-	-
6	1.25	888.8	0.1041	0.1853	2
6	1.50	1064.8	0.1061	0.1857	2
6	1.75	1240.8	0.1097	0.1854	2
6	2.00	1425.6	0.1142	0.1847	2
-	-	-	-	-	-
8	1.50	1064.8	0.1159	0.1863	2
8	1.75	1240.8	0.1176	0.1866	2
8	2.00	1425.6	0.1220	0.1867	2
10	1.50	1064.8	0.1258	0.1863	2
10	1.75	1240.8	0.1245	0.1870	2
10	2.00	1425.6	0.1277	0.1877	2

Region: Central

Batt. units	Scale	DC cap (kW)	Sys LCOE	AEP (USD/kWh)	Batt. repl.
1	0.25	202.4	0.0729	0.2016	0
1	0.50	404.8	0.0665	0.1946	1
1	0.75	607.2	0.0631	0.1893	1
1	1.00	800.8	0.0689	0.1859	2
1	1.25	1003.2	0.0760	0.1834	2
1	1.50	1205.6	0.0837	0.1816	2
1	1.75	1408.0	0.0920	0.1802	2
1	2.00	1601.6	0.1005	0.1794	2
2	0.50	404.8	0.0809	0.1948	1
2	0.75	607.2	0.0727	0.1897	1
2	1.00	800.8	0.0771	0.1868	2
2	1.25	1003.2	0.0833	0.1845	2
2	1.50	1205.6	0.0901	0.1827	2
2	1.75	1408.0	0.0981	0.1816	2
2	2.00	1601.6	0.1056	0.1806	2
3	0.75	607.2	0.0828	0.1901	1
3	1.00	800.8	0.0843	0.1873	2
3	1.25	1003.2	0.0901	0.1855	2
3	1.50	1205.6	0.0961	0.1838	2
3	1.75	1408.0	0.1037	0.1828	2
3	2.00	1601.6	0.1104	0.1817	2
4	1.00	800.8	0.0922	0.1879	2
4	1.25	1003.2	0.0955	0.1861	2
4	1.50	1205.6	0.1016	0.1848	2
4	1.75	1408.0	0.1076	0.1835	2
4	2.00	1601.6	0.1150	0.1829	2
6	1.00	800.8	0.1076	0.1886	2
6	1.25	1003.2	0.1071	0.1874	2
6	1.50	1205.6	0.1114	0.1865	2
6	1.75	1408.0	0.1164	0.1855	2
6	2.00	1601.6	0.1217	0.1846	2
8	1.25	1003.2	0.1172	0.1880	2
8	1.50	1205.6	0.1189	0.1875	2
8	1.75	1408.0	0.1239	0.1871	2
8	2.00	1601.6	0.1280	0.1863	2
10	1.50	1205.6	0.1276	0.1885	2
10	1.75	1408.0	0.1292	0.1880	2
10	2.00	1601.6	0.1344	0.1881	2

Investment appraisal results

The investment appraisal metrics as described in section 3.2 have been calculated for each of the modeled systems, and the results are presented in Tables 16, 17, 18, and 19 below. The Net Present Value, Internal Rate of Return and Payback Period have been calculated using the corresponding Equations 4, 5 and 6. Both the supplier perspective and the customer perspective of an outright purchase have been considered, by including or excluding a 30% margin to the CapEx (as explained in section 5.5). The NPV, IRR and Payback Period are analysed in section 6.1.2, to provide a broader perspective on which systems are most financially feasible for both the PV- and BESS system supplier and the customer.

To account for the supplier perspective of a PPA, the Profit Margin on the generated electricity has been calculated using the fixed discounted electricity price and LCOE in Equation 3.

Table 16: Systems without BESS / Outright Purchase & PPA: *NPV, IRR, and Payback Period*

	System & Investment		1x CapEx — No Net Metering				1x CapEx — With Net Metering				1.3x CapEx — No Net Metering				1.3x CapEx — With Net Metering			
DC Cap. (kW)	PV CapEx 1x (USD)	PV CapEx 1.3x (USD)	Yr1 savings (USD)	NPV (USD)	IRR	PP (yrs)	Yr1 savings (USD)	NPV (USD)	IRR	PP (yrs)	Yr1 savings (USD)	NPV (USD)	IRR	PB (yrs)	Yr1 savings (USD)	NPV (USD)	IRR	PB (yrs)
Region: West																		
184.8	73,920	96,096	40,832	269,957	55.2%	1.8	45,082	305,751	61.0%	1.6	38,105	224,812	39.6%	2.5	42,355	260,606	44.1%	2.3
360.8	144,320	187,616	74,943	486,832	51.9%	1.9	85,716	577,560	59.4%	1.7	69,618	398,692	37.1%	2.7	80,391	489,420	42.8%	2.3
536.8	214,720	279,136	101,956	643,925	47.5%	2.1	122,776	819,271	57.2%	1.7	94,033	512,789	33.7%	3.0	114,854	688,136	41.1%	2.4
712.8	285,120	370,656	119,135	718,201	41.8%	2.4	154,916	1,019,540	54.3%	1.8	108,615	544,071	29.3%	3.4	144,396	845,409	38.9%	2.6
888.8	355,520	462,176	122,763	678,359	34.5%	2.9	180,278	1,162,738	50.7%	2.0	109,646	461,233	23.6%	4.2	167,161	945,612	36.2%	2.8
1064.8	425,920	553,696	121,137	594,264	28.4%	3.5	203,013	1,283,805	47.7%	2.1	105,422	334,142	18.8%	5.3	187,298	1,023,684	33.8%	3.0
1240.8	496,320	645,216	117,328	491,787	23.5%	4.2	224,469	1,394,100	45.2%	2.2	99,016	188,670	14.9%	6.5	206,157	1,090,984	31.9%	3.1
1425.6	570,240	741,312	112,057	373,474	19.4%	5.1	246,504	1,505,754	43.2%	2.3	91,017	25,213	11.5%	8.1	225,464	1,157,492	30.4%	3.3
Region: Central																		
202.4	80,960	105,248	44,334	292,411	54.8%	1.8	48,994	331,654	60.5%	1.7	41,347	242,966	39.3%	2.5	46,007	282,209	43.7%	2.3
404.8	161,920	210,496	80,371	514,947	49.6%	2.0	93,599	626,344	57.8%	1.7	74,397	416,058	35.3%	2.8	87,624	527,455	41.6%	2.4
607.2	242,880	315,744	104,791	639,647	43.1%	2.3	132,746	875,073	54.7%	1.8	95,830	491,313	30.3%	3.3	123,785	726,739	39.2%	2.6
800.8	320,320	416,416	114,681	645,496	35.8%	2.8	163,131	1,053,527	50.9%	2.0	102,863	449,867	24.6%	4.0	151,312	857,899	36.3%	2.8
1003.2	401,280	521,664	116,062	576,161	28.9%	3.5	190,753	1,205,190	47.5%	2.1	101,256	331,088	19.2%	5.2	175,947	960,117	33.7%	3.0
1205.6	482,240	626,912	113,267	471,663	23.4%	4.3	215,839	1,335,501	44.8%	2.2	95,474	177,145	14.7%	6.6	198,046	1,040,983	31.6%	3.2
1408.0	563,200	732,160	108,000	346,349	18.9%	5.2	240,154	1,459,316	42.6%	2.3	87,220	2,387	11.0%	8.4	219,374	1,115,353	29.9%	3.3
1601.6	640,640	832,832	101,800	216,693	15.5%	6.3	262,481	1,569,905	41.0%	2.4	78,163	−174,564	8.0%	10.7	238,844	1,178,648	28.6%	3.5

Table 17: Systems without BESS / PPA: *Supplier Profit Margin, annual Profit and potential Net Metering Revenue*

Scale	DC Capacity (kW)	LCOE	Profit Margin	Annual Profit (USD/yr)	Potential NM Revenue (USD/yr)
Region: West					
0.25	184.8	0.0449	64.4%	19,833	4,250
0.50	360.8	0.0409	67.6%	38,718	10,773
0.75	536.8	0.0369	70.7%	56,253	20,821
1.00	712.8	0.0369	70.7%	67,802	35,781
1.25	888.8	0.0369	70.7%	73,598	57,515
1.50	1064.8	0.0369	70.7%	77,164	81,876
1.75	1240.8	0.0369	70.7%	79,773	107,141
2.00	1425.6	0.0369	70.7%	81,999	134,447
Region: Central					
0.25	202.4	0.0412	67.3%	22,570	4,660
0.50	404.8	0.0413	67.2%	41,714	13,227
0.75	607.2	0.0372	70.5%	58,942	27,954
1.00	800.8	0.0372	70.4%	67,748	48,450
1.25	1003.2	0.0372	70.5%	73,241	74,691
1.50	1205.6	0.0373	70.4%	76,886	102,572
1.75	1408.0	0.0372	70.5%	79,565	132,154
2.00	1601.6	0.0372	70.4%	81,583	160,681

Table 18: Systems with BESS / Outright Purchase & PPA: *NPV, IRR, and Payback Period*

Region: West

		Financial Metrics — 1x capex				Financial Metrics — 1.3x capex			
Batt mod.	**DC cap (kW)**	**CapEx (USD)**	**NPV (USD)**	**IRR (%)**	**PB (yrs)**	**CapEx (USD)**	**NPV (USD)**	**IRR (%)**	**PB (yrs)**
	184.8	143,660	321,533	38.22	3	186,758	247,498	27.38	4
	360.8	213,620	522,893	40.67	3	277,706	406,538	29.01	4
	536.8	265,980	720,424	44.11	3	345,774	566,911	31.40	4
1	712.8	336,380	791,664	40.10	3	437,294	584,855	27.92	4
	888.8	406,780	773,828	34.64	3	528,814	517,802	23.48	5
	1064.8	477,180	705,116	29.48	4	620,334	405,627	19.44	5
	1240.8	547,580	611,970	25.08	4	711,854	270,157	15.97	6
	1425.6	621,500	494,661	21.14	5	807,950	108,569	12.80	8
	360.8	264,880	474,012	32.91	4	344,344	340,088	23.34	5
	536.8	317,240	669,875	37.15	3	412,412	497,313	26.34	4
	712.8	387,640	733,886	34.96	3	503,932	499,681	23.99	5
2	888.8	458,040	714,973	30.90	4	595,452	424,271	20.42	5
	1064.8	528,440	645,200	26.64	4	686,972	305,575	16.93	6
	1240.8	598,840	558,735	23.03	5	778,492	176,160	14.06	7
	1425.6	672,760	436,992	19.42	5	874,588	6,401	11.10	9
	536.8	368,500	613,156	31.93	4	479,050	422,039	22.49	5
	712.8	438,900	698,696	31.24	4	570,570	447,187	21.33	5
3	888.8	509,300	652,823	27.72	4	662,090	329,576	17.80	6
	1064.8	579,700	583,643	24.17	4	753,610	207,041	14.77	7
	1240.8	650,100	497,927	21.09	5	845,130	75,691	12.25	8
	1425.6	724,020	374,316	17.83	6	941,226	−97,949	9.54	11
	712.8	490,160	636,906	27.83	4	637,208	363,095	18.71	6
	888.8	560,560	602,907	25.36	4	728,728	252,542	15.91	6
4	1064.8	630,960	519,231	22.00	5	820,248	105,828	12.83	7
	1240.8	701,360	434,986	19.34	5	911,768	−26,206	10.59	8
	1425.6	775,280	332,682	16.82	6	1,007,864	−174,385	8.48	12
	-	-	-	-	-	-	-	-	-
	888.8	663,080	492,336	21.35	5	862,004	92,426	12.63	7
6	1064.8	733,480	413,631	18.90	5	953,524	−61,867	10.01	8
	1240.8	803,880	319,715	16.55	6	1,045,044	−214,170	7.90	12
	1425.6	877,800	211,812	14.39	6	1,141,140	−373,043	5.99	14
	-	-	-	-	-	-	-	-	-
8	1064.8	836,000	319,189	16.57	6	1,086,800	−207,163	7.89	9
	1240.8	906,400	228,791	14.68	6	1,178,320	−365,811	5.96	14
	1425.6	980,320	102,550	12.52	7	1,274,416	−554,470	3.99	16
	1064.8	938,520	222,159	14.60	6	1,220,076	−346,808	5.97	10
10	1240.8	1,008,920	151,947	13.29	7	1,311,596	−492,507	4.41	16
	1425.6	1,082,840	24,768	11.35	7	1,407,692	−690,649	2.48	17

Region: Central

		Financial Metrics — 1x capex				Financial Metrics — 1.3x capex			
Batt mod.	**DC cap (kW)**	**CapEx (USD)**	**NPV (USD)**	**IRR (%)**	**PB (yrs)**	**CapEx (USD)**	**NPV (USD)**	**IRR (%)**	**PB (yrs)**
	202.4	142,340	398,292	44.86	3	185,042	325,296	32.53	4
	404.8	233,420	579,187	41.50	3	303,446	443,431	29.34	4
	607.2	294,140	730,095	41.48	3	382,382	553,138	29.11	4
1	800.8	371,580	736,424	35.60	3	483,054	507,256	24.38	5
	1003.2	452,540	684,491	29.90	4	588,302	404,477	19.87	5
	1205.6	533,500	594,811	25.06	4	693,550	265,568	16.03	6
	1408.0	614,460	479,040	20.95	5	798,798	101,230	12.70	8
	1601.6	691,900	347,084	17.48	6	899,470	−78,664	9.80	10
	404.8	284,680	522,514	34.07	3	370,084	366,085	23.85	5
	607.2	345,400	683,861	35.81	3	449,020	479,347	24.76	4
	800.8	422,840	686,866	31.68	4	549,692	423,531	21.18	5
2	1003.2	503,800	630,725	27.04	4	654,940	313,891	17.40	6
	1205.6	584,760	543,296	23.01	5	760,188	176,589	14.16	7
	1408.0	665,720	421,877	19.26	5	865,436	3,521	11.06	8
	1601.6	743,160	297,304	16.28	6	966,108	−167,526	8.55	11
	607.2	396,660	627,203	31.22	4	515,658	397,935	21.23	5
	800.8	474,100	641,742	28.63	4	616,330	349,028	18.76	6
3	1003.2	555,060	576,298	24.62	4	721,578	223,614	15.28	6
	1205.6	636,020	488,459	21.16	5	826,826	84,561	12.44	8
	1408.0	716,980	364,047	17.76	6	932,074	−93,154	9.58	11
	1601.6	794,420	242,270	15.11	7	1,032,746	−261,598	7.31	12
	800.8	525,360	585,523	25.88	4	682,968	263,346	16.48	6
	1003.2	606,320	535,732	22.86	5	788,216	152,859	13.78	7
4	1205.6	687,280	434,764	19.55	5	893,464	−5,607	10.91	8
	1408.0	768,240	325,938	16.79	6	998,712	−164,240	8.57	9
	1601.6	845,680	185,843	14.02	7	1,099,384	−356,814	6.14	14
	800.8	627,880	466,106	21.38	5	816,244	90,176	12.69	7
	1003.2	708,840	430,741	19.50	5	921,492	−15,317	10.75	8
6	1205.6	789,800	331,292	16.89	6	1,026,740	−178,428	8.33	9
	1408.0	870,760	219,359	14.58	7	1,131,988	−344,008	6.24	14
	1601.6	948,200	101,289	12.53	7	1,232,660	−509,849	4.38	15
	1003.2	811,360	337,622	17.07	6	1,054,768	−160,220	8.50	9
8	1205.6	892,320	251,212	15.13	6	1,160,016	−317,519	6.48	10
	1408.0	973,280	120,976	12.82	7	1,265,264	−511,204	4.30	16
	1601.6	1,050,720	6,677	11.09	8	1,365,936	−674,822	2.62	17
	1205.6	994,840	146,085	13.23	7	1,293,292	−482,119	4.42	16
10	1408.0	1,075,800	51,077	11.73	7	1,398,540	−637,966	2.81	17
	1601.6	1,153,240	−97,422	9.71	8	1,499,212	−849,453	0.83	19

Note: Battery replacements column removed — all systems with scaling ≥1.0 require 2 replacements; see Table 14 for details.

Table 19: Systems with BESS / PPA: *Supplier Profit Margin and annual Profit*

Region: West

Batt. units	Scale	DC cap (kW)	Sys LCOE	Profit margin	Ann. profit (USD/yr)	Batt. repl.
1	0.25	184.8	0.0802	36.3%	11,580	0
1	0.50	360.8	0.0659	47.7%	27,604	0
1	0.75	536.8	0.0598	52.5%	43,305	1
1	1.00	712.8	0.0627	50.2%	51,212	2
1	1.25	888.8	0.0680	46.0%	52,503	2
1	1.50	1064.8	0.0746	40.8%	49,402	2
1	1.75	1240.8	0.0817	35.2%	44,377	2
1	2.00	1425.6	0.0895	29.0%	37,668	2
2	0.50	360.8	0.0802	36.3%	21,582	0
2	0.75	536.8	0.0706	44.0%	37,032	1
2	1.00	712.8	0.0721	42.8%	45,044	2
2	1.25	888.8	0.0759	39.7%	47,387	2
2	1.50	1064.8	0.0818	35.1%	44,784	2
2	1.75	1240.8	0.0878	30.3%	40,401	2
2	2.00	1425.6	0.0953	24.3%	33,494	2
3	0.75	536.8	0.0815	35.3%	30,115	1
3	1.00	712.8	0.0789	37.3%	40,255	1
3	1.25	888.8	0.0838	33.5%	41,370	2
3	1.50	1064.8	0.0885	29.7%	39,567	2
3	1.75	1240.8	0.0938	25.5%	35,594	2
3	2.00	1425.6	0.1010	19.9%	28,655	2
4	1.00	712.8	0.0880	30.1%	32,998	1
4	1.25	888.8	0.0905	28.2%	35,906	2
4	1.50	1064.8	0.0951	24.5%	33,860	2
4	1.75	1240.8	0.0996	21.0%	30,449	2
4	2.00	1425.6	0.1049	16.8%	25,232	2
-	-	-	-	-	-	
6	1.25	888.8	0.1041	17.4%	23,152	2
6	1.50	1064.8	0.1061	15.8%	23,307	2
6	1.75	1240.8	0.1097	12.9%	20,236	2
6	2.00	1425.6	0.1142	9.4%	15,266	2
-	-	-	-	-	-	
8	1.50	1064.8	0.1159	8.0%	12,431	2
8	1.75	1240.8	0.1176	6.7%	11,122	2
8	2.00	1425.6	0.1220	3.2%	5,577	2
10	1.50	1064.8	0.1258	0.2%	254	2
10	1.75	1240.8	0.1245	1.2%	2,097	2
10	2.00	1425.6	0.1277	-1.3%	-2,459	2

Region: Central

Batt. units	Scale	DC cap (kW)	Sys LCOE	Profit margin	Ann. profit (USD/yr)	Batt. repl.
1	0.25	202.4	0.0729	42.1%	14,773	0
1	0.50	404.8	0.0665	47.2%	30,604	1
1	0.75	607.2	0.0631	49.9%	43,598	1
1	1.00	800.8	0.0689	45.3%	46,204	2
1	1.25	1003.2	0.0760	39.7%	44,525	2
1	1.50	1205.6	0.0837	33.6%	40,041	2
1	1.75	1408.0	0.0920	27.0%	33,617	2
1	2.00	1601.6	0.1005	20.3%	25,974	2
2	0.50	404.8	0.0809	35.8%	23,834	1
2	0.75	607.2	0.0727	42.3%	38,710	1
2	1.00	800.8	0.0771	38.8%	41,734	2
2	1.25	1003.2	0.0833	33.9%	40,055	2
2	1.50	1205.6	0.0901	28.5%	35,806	2
2	1.75	1408.0	0.0981	22.1%	29,038	2
2	2.00	1601.6	0.1056	16.2%	21,912	2
3	0.75	607.2	0.0828	34.3%	32,312	1
3	1.00	800.8	0.0843	33.1%	37,173	2
3	1.25	1003.2	0.0901	28.5%	35,280	2
3	1.50	1205.6	0.0961	23.7%	31,265	2
3	1.75	1408.0	0.1037	17.7%	24,345	2
3	2.00	1601.6	0.1104	12.3%	17,470	2
4	1.00	800.8	0.0922	26.8%	31,252	2
4	1.25	1003.2	0.0955	24.2%	31,311	2
4	1.50	1205.6	0.1016	19.3%	26,613	2
4	1.75	1408.0	0.1076	14.6%	21,015	2
4	2.00	1601.6	0.1150	8.7%	12,861	2
6	1.00	800.8	0.1076	14.6%	17,895	2
6	1.25	1003.2	0.1071	15.0%	20,883	2
6	1.50	1205.6	0.1114	11.5%	17,203	2
6	1.75	1408.0	0.1164	7.6%	11,833	2
6	2.00	1601.6	0.1217	3.4%	5,517	2
8	1.25	1003.2	0.1172	7.0%	10,253	2
8	1.50	1205.6	0.1189	5.6%	8,968	2
8	1.75	1408.0	0.1239	1.7%	2,836	2
8	2.00	1601.6	0.1280	-1.6%	-2,796	2
10	1.50	1205.6	0.1276	-1.3%	-2,156	2
10	1.75	1408.0	0.1292	-2.6%	-4,582	2
10	2.00	1601.6	0.1344	-6.7%	-12,321	2

6 Analysis

This chapter analyses the empirical findings using the selected frameworks, to evaluate the feasibility of Solar Photovoltaic (PV) in tea manufacturing and directly answer the research questions.

6.1. Techno-economic analysis

Technical feasibility

The results from the simulations by Delden and the empirical findings from interviews and observations during the field study indicate that solar PV energy systems are technically feasible for integration within the Kenyan tea manufacturing industry. Across all evaluated cases, the optimized systems were able to contribute a significant share of the electricity demand, while operating within realistic system boundaries and operational conditions as defined in section 3.2.

One of the main factors that support the technical feasibility is the strong solar resource potential in Kenya, as highlighted in section 2.3.4. Both assessed regions possess relatively stable solar irradiance levels across all seasons, which creates favorable conditions for integrating solar energy in industrial settings where generation is relatively constant over the year. The simulation results further supports this, and although there are some regional variations in both solar irradiation patterns and electricity load between Region West and Region Central, the differences in technical performance were relatively small. This indicates that solar PV systems can be implemented across several tea-producing regions in Kenya without any major variations in performance.

Another important aspect is the compatibility between the solar PV generation pattern and the electricity consumption pattern of a tea factory. As demonstrated in Figures 14a and 14b, and as discussed in section 5.3.2, tea factories have a relatively high electricity demand during nighttime and early mornings. This limits the possibility of utilizing solar energy to cover the whole operational load. The average curtailment as simulated by Delden is prominent, and as shown in Table 8, even though the systems are optimized based on both load and weather data, some of the larger PV systems may have a utilization degree of only around 40%. Moreover, solar generation is intermittent and dependent on weather conditions, so despite the arguably good operational conditions in Kenya, tea factories cannot fully depend on a solar PV system to satisfy the electricity demand. Grid electricity remains necessary to ensure operational reliability outside daytime hours and in periods of low irradiation. However, as shown in section 5.2.2, a large share of the electricity demand still occurs during the day, and complies well with the peak solar irradiation hours. Therefore, a large share of the electricity generated by a PV system can be consumed directly within the manufacturing process. Figures 14a and 14b clearly displays this. Moreover, by combining a PV system with a Battery Energy Storage System or assuming Net Metering is possible, a larger share of the generated electricity can be either consumed or sold. Whether or not Net Metering will become realistically possible for tea factories in Kenya is highly uncertain, and if it does, there are technical and regulatory limitations to the extent it can be utilized. As already highlighted under 5.1.4, qualified projects are limited to 1 MW. Moreover, the size of the power system must be scaled according to peak load. If considering Net Metering regulations, there are thus direct restrictions affecting the flexibility in the technical feasibility, limiting the possible system setups to those scaled 0.25-1.0 times the peak load.

In addition to the operational factors, practical constraints must also be considered when evaluating technical feasibility. Given that a grid-tied PV system cannot operate when power outages occur on the grid, the PV energy systems is in practice technically limited during periods of instability - a quite common occurrence in Kenya. Installation constraints, such as available roof area, structural conditions and geographic location, influence the feasible PV capacity, highlighted by e.g., [I7]. Of course, these factors are highly case-specific and are not considered as definitive for this study. However, they are critical in real implementation projects. Particularly the larger systems assessed in this report may be unfeasible for installation on some of the tea factories considered. As described in section 2.3.3, the solar PV panels have an area of approximately 2.59 m^2 and a weight of 31.8 kg. The largest PV systems consist of 162 strings with panels for Region West, and 182 strings for Region Central. Given that each string consists of 16 panels, the PV systems would have a total area of around 6,713 m^2 for West and 7,542 m^2 for Central. The weight of the systems would be 82,426 or 92,602 kg respectively. The roof structure of the tea factory in consideration is therefore a crucial factor when determining technical feasibility. It must be large enough to hold the area of the PV system, and sturdy enough to hold the weight. Based on observations during site visits, it is clear that this is likely to be a concern for the larger systems as all visited factories had simple sheet metal roofs. Moreover, the battery modules weigh 2,700 kg each. A BESS with 10 modules would weight a total of 27,000 kg, and locating an appropriate place with the neccessary structural mechanics and strength for installment of such a heavy system within a tea factory could be difficult. Nevertheless, these practical installation factors are highly case-specific and dependent on the individual factory and the scale of the system as a whole, and does not directly oppose the technical feasibility of solar PV in the Kenyan tea industry.

Overall, the empirical findings and simulation results indicate that solar PV systems are technically feasible for tea factories in Kenya. The strongest technical potential appears in systems that are carefully sized according to factory demand profiles and operational conditions, thereby maximizing self-consumption while minimizing surplus generation, or a slightly upscaled PV system combined with a BESS.

Financial feasibility

As mentioned in section 3.2.2, there are several financial metrics that can be considered when identifying the most profitable investment. The key metrics needed for analysing the results vary depending on the financial model and whether the supplier or customer perspective is in focus. A summary of the main financial findings can be found in Table 20 at the end of this analysis.

1. **Base Case:** The base case scenario is relevant for the customer perspective, to function as a relative number when comparing the AEP. As defined in 5.1.4, the grid price is 0.21 USD/kWh in both the West and Central regions, but the diesel consumption varied. The AEP for a tea factory located in either region is thus the grid price + the cost of diesel used in the backup generator. Since the diesel consumption is higher in the central region compared to the west, the AEP there is also higher. The AEP results presented in Table 11 are arguably feasible, since they reflect the current situation. However, as already mentioned in section 5.3.3, tea industry stakeholders are not pleased with the current cost of electricity, which supports the assessment of other system setups.
2. **Grid-tied PV system, without Net Metering and BESS:**
    - **Supplier Perspective / Outright Purchase:** In an outright purchase, there is a clear pattern indicating that the larger the PV system, the larger the cash flow for the supplier. This is due to the 30% CapEx margin that is added for the customer. For the supplier to achieve the highest revenue, a system size within the higher scaling range of 0.75-2.0 should be considered in both region, since those would provide the largest cash flow. Even though larger systems are financially beneficial for the supplier, the customer perspective needs to be considered to match system performance expectations. With a larger system, higher upfront investment costs follow, risking that several tea factories cannot invest due to the economic barriers mentioned in section 5.3.3. Taking this into consideration, the most optimal PV system for the supplier is reflected by those most attractive for the customer. In Region West, should range between 536.8 kW (scale 0.75) and 1064.8 kW (scale 1.5). For Region Central, the most optimal system sizes range between 607.2 kW (scale 0.75) and 1003.2 kW (scale 1.25). Since Region Central has slightly larger systems compared to Region West, the CapEx is higher, resulting in greater potential earnings for the supplier.
    - **Customer Perspective / Outright Purchase:** The results for the grid-tied PV system without Net Metering and BESS are presented in Table 12 and show clear financial potential from a customer perspective in an outright purchase model. For the customer price, the results for the 1.3x CapEx needs to be considered since it includes the supplier margin. To begin with, the results indicate that all analysed PV systems have a lower AEP compared to the base case presented in Table 11. However, it is also clear that the financial benefit depends on the size of the system. In Region West, the system sizes with the lowest AEP range between 712.8 kW (scale 1.0) and 1064.8 kW (scale 1.5), where the lowest AEP is achieved at scale 1.25, corresponding to 888.8 kW DC capacity and an AEP of 0.1668 USD/kWh. This represents a reduction of approximately 22% compared with the base case AEP of 0.2144 USD/kWh. Since Net Metering is not accounted for in this scenario, the system limit of scaling it to the peak load does not need to be considered, meaning that the system with 1064.8 kW DC capacity can be optimal. On the other hand, if Net Metering is later implemented, a system within the scaling range of 0.25-1.0 may be a better option. This will be further discussed below. In Region Central, the lowest AEP was found for the system sizes 800.8 kW (scaling factor 1.0) to 1003.2 kW (scaling factor 1.25). The lowest AEP is

achieved at scale 1.0, corresponding to 800.8 kW DC capacity and an AEP of 0.1708 USD/kWh, which is approximately 21% lower than the base case AEP of 0.2151 USD/kWh. Since this system is also within the Net Metering limit compared to the system at scale 1.25, Net Metering could be implemented in the future. The results indicate that an optimally sized PV system can substantially reduce electricity costs for tea factories. On the other hand, the results show that larger systems are not necessarily financially attractive since the surplus electricity produced cannot currently be utilized. The investment appraisal results further support these conclusions. For Region West, the strongest financial performance is observed around 712.8 kW (scale 1.0), where the NPV reaches 544,071 USD, the IRR is 29.3%, and the payback period is 3.4 years. In Region Central, the strongest NPV is found at 607.2 kW (scale 0.75), with an NPV of 491,313 USD, IRR of 30.3%, and payback period of 3.3 years. These financial results emphasize choosing a system scaled to the peak load since moderately sized systems not only have positive NPV values, but also higher ones. In addition, IRR exceeds the assumed discount rate, and the payback period is relatively short, ensuring financially defendable investment potentials. By comparing the two regions, Region West is the most profitable region from a customer perspective. It reaches a lower minimum AEP and has the strongest investment appraisal result compared to Region Central.

- **Supplier Perspective / Power Purchasing Agreement:** From a supplier perspective, under PPA, a grid-tied PV system, both without Net Metering and BESS, appears financially attractive based on the results in Table 17. In this model, it is the supplier (Miale) that carries the upfront investment cost and the operational expenses, while the revenue is based on the fixed discounted electricity price to the customer. The results are based on a discounted PPA price of 0.126 USD/kWh, corresponding to 60% of the KPLC grid price. The results show that the calculated PV LCOE values for 1.0x CapEx are all lower than the PPA price, resulting in a higher profit margin for the supplier. In Region West, the LCOE values range between 0.0449 and 0.0369 USD/kWh, resulting in a potential profit margin of 64.36% to 70.72%. For the central region, the LCOE ranges between 0.0413 and 0.0372 USD/kWh, corresponding to a profit margin of 67.34% to 70.44% for Miale. For both regions, the highest margins are found for the systems within the system scale of 0.75-2.0, and the potential profits are slightly higher in Region West. Overall, these results indicate strong financial potential from a supplier perspective since each kWh sold under the PPA contributes positively to the project's earnings. On the other hand, the supplier still needs to be aware that their profitability strongly depends on how much of the generated electricity from the system can be sold to the factory. In this scenario, neither Net Metering nor battery storage is included, which means that the produced excess electricity cannot be utilized or sold to the grid. Taking this into consideration, the most financially attractive system is not necessarily the largest, indicating the importance of a balance in installed capacity, direct power consumption at the factory and investment return. Lastly, the investment appraisal metrics should be used to identify the most financially defendable system size. For Region West, the strongest financial performance is observed around 712.8 kW (scale 1.0), where the NPV reaches 544,071 USD, the IRR is 41.8%, and the payback period is 2.4 years. For Region Central, two of the systems show the most potential. The most optimal values are found for the system with 607.2 kW (scale 0.75) with NPV of 639,647 USD, IRR 43.1% and a payback time of 2.3 years. The second system with 800.8 kW has a NPV of 645,496 USD, an IRR of 35.8% and a payback time of 2.8 years. This means that Region Central shows stronger NPV values in the investment appraisal. Overall, the PPA model appears financially feasible for the supplier, but its attractiveness depends on careful system sizing and a stable long-term agreement with the customer.

- **Customer Perspective / Power Purchasing Agreement:** By analysing the PPA from a customer perspective, it is shown to be financially attractive since it reduces the AEP without the requirement of an upfront investment. The most important metric for the customer in this case is the AEP, since it directly shows whether the PPA model reduces the factory's electricity cost compared with the base case. By comparing the results in Table 14 to the base case results in Table 11, it is shown that the grid-tied PV system without Net Metering and without BESS reduces the AEP in both regions. In Region West, the PPA AEP values range from 0.2057 USD/kWh (for system scale 0.25) and 0.1809 USD/kWh (for system scale 2.0). Compared to the base case, this corresponds to a reduction of approximately 4.1% to 15.6% in costs. For Region Central, the smallest system (scale 0.25) has a PPA AEP of 0.2059 USD/kWh, and the largest system (scale 2.0) has 0.1820 USD/kWh. This corresponds to a cost reduction of approximately 4.3% to 15.4% compared to the base case. This indicates that the PPA model can provide direct electricity cost savings for tea factories without exposing them to investment risk. Region West is slightly more profitable since the PPA AEP is lower compared to Region Central, but the difference is very small.

3. **Grid-tied PV system, with Net Metering and without BESS:**
    - **Supplier Perspective / Outright Purchase:** The financial benefit for the supplier under an outright purchase agreement follows the same trend as described in the previous scenario without Net Metering. This means that a larger PV system results in higher revenue for the supplier. The results in Table 12 show that Net Metering strengthens the commercial attractiveness of larger systems compared to the previous scenario. This is mainly due to Net Metering allowing surplus electricity to create value instead of being curtailed. As mentioned, this study assumes that each kWh sold to the grid generates an income of 0.105 USD/kWh. However, as described in the previous section 6.1.1, there are factors that limit the Net Metering implementation, such as peak load scaling and system capacity. To increase customer attractiveness, the PV system should meet the requirements of not exceeding the capacity of the factory´s peak load or 1 MW. Overall, the scenario is financially attractive in both regions for the supplier under an outright purchase model.
    - **Customer Perspective / Outright Purchase:** By analysing the AEP results in Table 12, implementing Net Metering to the PV systems analysed in the previous scenario would result

in lower AEP values. The results show a clear trend that the AEP decreases as PV system size increases. By selling back the generated excess electricity to the grid for 50% of the KPLC price, results in an AEP of 0.1516 USD/kWh for the largest accepted system in Region West. Compared to the base case, this corresponds to a reduction of approximately 29%. For Region Central, the largest PV systems that meet the criteria for Net Metering have an AEP of 0.1498 USD/kWh, which means a reduction of approximately 30%. Moreover, the investment appraisal results in Table 16 confirm the financial feasibility for this scenario. The NPV value for the PV system scaled for the peak load, 712.8 kW, in Region West is 845,409 USD. In addition, the system has an IRR of 38.9% and a payback period of 2.6 years. For Region Centrals, the optimal PV system at 800.8 kW reaches an NPV of 857,899 USD, an IRR of 36.3% and a payback period of 2.8 years. These results indicate that the investment is financially defendable, as the NPV is strongly positive, the IRR exceeds the assumed discount rate, and the payback period is relatively short. However, the results also show that the payback period increases and the IRR decreases with system size despite high NPV. This means that larger systems generate higher total value, but each additional unit of capacity contributes a lower marginal return. In this case, it is also shown that Region Central is the most profitable region, since the larger system sizes generate higher sales revenue. In addition, Net Metering increases the attractiveness of larger PV systems. Overall, the customer perspective for an outright purchase with Net Metering is highly positive.

- **Supplier Perspective / Power Purchasing Agreement:** As described in the previous scenario, without Net Metering, the financial benefit for the supplier in a PPA is mainly decided based on the profit margins. For this scenario, which includes Net Metering, the profit margins will increase further since the results indicate a potential revenue that increases with the size of the PV system. Since Net Metering is limited for systems that are scaled to their peak load (scaling factor 1.0), the maximum annual revenue for the supplier is 35,781 USD in Region West and 48,450 USD in Region Central. In addition, the investment appraisal metrics in Table 18 should be used to identify a financially defendable system size. For both regions, the NPV increases with PV system size. At the same time, the IRR decreases with system size and the payback time increases. The NPV is positive for all analysed system sizes in both regions, meaning that all PV systems would be a good investment. In this case, the most interesting results are for the two PV systems scaled to the factory's peak load. For Region West, the NPV for a 712.8 kW system is 1,019,540 USD, the IRR 54.3%, and the payback time 1.8 years. For Region Central, the strongest financial performance is observed for a system with a DC capacity of 800.8 kW. Its NPV is 1,053,527 USD with an IRR of 50.9% and a payback time of 2.0 years. These results clearly indicate that the PPA model is financially attractive for the supplier, since the investment generates high discounted returns and the initial capital is recovered within a very short period. In addition, the IRR value is above Miale's limit at 18% to proceed with a project. By comparing the two regions, Region Central is shown to be the most profitable region, since both the potential Net Metering revenue and NPV is higher compared to the values in Region West.

- **Customer Perspective / Power Purchasing Agreement:** For a PV system with Net Metering, the customer does not receive direct revenue from selling back excess generated electricity to the grid under a PPA. The reason is that the supplier covers the capital investment and operational costs, while the customer only purchases the electricity consumed on site at the agreed discounted PPA price. Since the PV system would be owned by the supplier during the PPA period, the potential extra revenue or credit from sold electricity belongs to the supplier unless anything else is specified in the contract. For the customer, this means that the financial benefit is the same as for the previous scenario without Net Metering. This means that Region West remains slightly more favourable in this case as well. Overall, the PPA comes with upsides for the customer since the electricity costs are lowered compared to the base case. In addition, the customer avoids large upfront investment costs, which enables more factories to invest now.

4. **Grid-tied PV system, with BESS:**
   - **Supplier Perspective / Outright Purchase:** As mentioned, for an outright purchase, the system is sold directly to the customer. This means that the most critical metric is a high profit margin for the supplier. In this study, receives a 30% markup on the baseline CapEx for both the PV system and BESS. This means that a larger PV system that includes a higher number of battery modules results in a higher potential revenue for the supplier. Thus, Region Central is the most profitable region since it requires larger systems compared to Region West. However, the system size must be balanced against customer attractiveness since high CapEx can become a major barrier for the customer who is responsible for financing the full upfront investment. Therefore, it is important to understand the customer perspective analysed in the next paragraph.
   - **Customer Perspective / Outright Purchase:** Since the customer purchases the PV system with BESS directly, the 1.3x CapEx results are relevant, as they include the supplier margin and therefore represent the actual customer investment cost. Therefore, the number of battery replacements during the system lifetime has a significant impact on the total lifetime cost and investment appraisal results. For this scenario, the BESS increases self-consumption for the customer since the surplus electricity from the PV system can be stored and utilized later. This reduces the amount of electricity bought from KPLC and lowers the AEP for all systems in Table 14 compared to the base case presented in Table 11. For Region West, the lowest AEP values are achieved by the system setups: 1064.8 kW DC capacity (scale 1.5) with 10 battery modules, 1240.8 kW DC capacity (scale 1.75) with 10 battery modules, 1064.8 kW DC capacity (scale 1.5) with 8 battery modules and lastly 888.8 kW DC capacity (scale 1.25) with 6 battery modules. The lowest AEP is found for the first mentioned system scaled 1.5 times the factory's peak load with 10 battery modules, reaching 0.1555 USD/kWh. However, the difference between the best alternatives is small and the investment appraisal results in Table 18 need to be considered before

identifying the most financially optimal system. By analysing these results, it is shown that only the system setup with a DC capacity of 888.8 kW and 6 battery units is financially defendable since all other systems have a negative NPV. This system reaches a NPV of 92,426 USD, has an IRR of 12.63% and a payback time of 7 years. However, even if the NPV and the IRR values of this system are positive, they are relatively low. While no specific target for these numbers have been defined, there could be concerns related to for instance the IRR compared to the cost of capital. This argues for decreasing the number of battery modules. It is clear that there is a trade-off between a low AEP and high investment appraisal metrics, and while AEP is slighly higher, the NPV and IRR is significantly better for the same system with e.g., 1 or 2 battery modules. For Region Central, the lowest AEP values are achieved by the system setups: 1205.6 kW DC capacity (scale 1.5) with 10 battery modules, 1003.2 kW (scale 1.25) with 8 battery modules, 1205.6 kW (scale 1.5) with 8 battery modules, 1408 kW (scale 1.75) with 10 battery modules, 1003.2 kW (scale 1.25) with 6 battery modules, and lastly 1,003.2 kW (scale 1.25) with 4 battery modules. The appraisal investment results in Table 18 indicate that only one of these options are financially defendable. All system setups except for the system with scaling factor 1.25 and 4 battery units have negative NPV. This means that the most optimal system from a customer perspective has a DC capacity of 1,003.2 kW with 4 battery units, reaching a NPV of 152,859 USD, an IRR of 13.78% and a payback time of 7 years. As for the Region Wast, IRR is not necessarily financially viable despite the positive NPV value. A better middle-way for low AEP and more beneficial investment apraisal metrics would be to decrease to one or two battery modules. The results show that Region West can reach a lower AEP compared to Region Central. On the other hand, Region Central is the most profitable region when NPV is considered since the NPV is higher.

- **Supplier Perspective / Power Purchasing Agreement:** As mentioned, a PPA for a supplier means that they carry both the CapEx and OpEx costs, while revenue is generated by selling electricity to the customer at the agreed PPA price. Net Metering is not considered in this case which means that the profitability depends on how much PV and battery electricity can be sold directly to the factory. The results in Table 19 show that the most financially attractive PV systems are moderately scaled to the peak load with a limited number of battery modules. In Region West, the highest annual profit is achieved with one battery module and 888.8 kW DC capacity (scale 1.25), generating 52,503 USD/year with a profit margin of 46.0%. In Region Central, the highest annual profit is achieved with one battery module and 800.8 kW DC capacity (scale 1.0), generating 46,204 USD/year with a profit margin of 45.3%. In addition, the investment appraisal metrics in Table 18 should be considered to identify a financially defendable system size. Similar to the annual profit results, the investment appraisal results show that the highest NPV for each battery configuration is generally achieved at a moderately scaled PV system rather than at the largest installed capacity. In Region West, the strongest performance is achieved by the 712.8 kW system (scale 1.0) with one battery module, yielding an NPV of 791,664 USD, an IRR of 40.10%, and a payback period of 3 years. In Region Central, the highest NPV is achieved by the 800.8 kW system (scale 1.0) with one battery module, with an NPV of 736,424 USD, an IRR of 35.60%, and a payback period of 3 years. These results indicate that Region West is the most profitable region since it gives the highest annual profit and a stronger NPV. Overall, the results indicate that the PPA model is financially defendable for the supplier in both regions when the BESS capacity is limited and well matched to the factory load.

- **Customer Perspective / Power Purchasing Agreement:** For a PPA, the most relevant financial metric is the AEP presented in Table 13 in comparison to the base case results in Table 11. Since both CapEx and OpEx costs are covered by the supplier, the potential customer investment is not affected by NPV, IRR and the payback period. The results indicate that all relevant system PPA configurations reduce the AEP compared to the base case, with an AEP of 0.2144 USD/kWh for Region West and 0.2151 USD/kWh for Region Central. There is a clear trend showing that AEP decreases for larger PV systems with fewer battery modules. This means that all PV systems scaled to the peak load or higher (1.0-2.0) should be considered from a customer perspective since they are more financially beneficial. In Region West, the lowest AEP is achieved with one battery module and a PV DC capacity of 1,425.6 kW (scale 2.0), reaching 0.1783 USD/kWh. This corresponds to a cost reduction of approximately 16.8% compared to the base case. In Region Central, the lowest AEP is also achieved with one battery module and the largest modeled PV system, 1,601.6 kW (scale 2.0), reaching 0.1794 USD/kWh. In comparison with the base case, this means a cost reduction of approximately 16.6%. This result indicates that a limited BESS configuration is more attractive than maximizing battery capacity. It also shows that Region West is slightly more profitable since the lowest PPA AEP is lower compared to Region Central. On the other hand, the difference is very small. Overall, a PPA for a PV system with BESS is financially feasible from the customer perspective in both regions. The advantages of the model are that electricity costs are reduced compared to the base case setup while investment risks and responsibilities for operation and battery replacements are avoided.

Table 20: Summary of main financial findings

Scenario	Customer perspective	Supplier perspective	Main implication
PV without Net Metering, outright purchase	Attractive when sized close to demand. Lowest AEP is about 0.1668 USD/kWh in West and 0.1708 USD/kWh in Central.	Larger systems increase revenue through the 30% CapEx margin, but high upfront cost may reduce customer interest.	Good case, but oversizing should be avoided since surplus electricity has no value.
PV without Net Metering, PPA	Lowers AEP without upfront investment, reaching about 0.1809 USD/kWh in West and 0.1820 USD/kWh in Central.	Strong margins because PV LCOE is below the PPA price of 0.126 USD/kWh.	Attractive for both sides if most generated electricity is consumed onsite.
PV with Net Metering, outright purchase	Strongest customer case. AEP falls to 0.1516 USD/kWh in West and 0.1498 USD/kWh in Central.	Larger systems become more attractive since surplus electricity creates value.	Best customer option, with AEP reductions of about 29–30% within net metering limits.
PV with Net Metering, PPA	Customer benefit depends on whether net metering value is included in the PPA contract.	Strongest supplier case, with NPV up to 1.02 MUSD in West and 1.05 MUSD in Central.	Contract design decides how the net metering value is shared.
PV with BESS, outright purchase	BESS lowers AEP, but battery costs weaken returns. Defendable cases give NPVs of 92,426 USD in West and 152,859 USD in Central.	Higher CapEx increases revenue, but battery cost makes the customer case weaker.	Financially weaker than net metering; BESS capacity should be limited.
PV with BESS, PPA	Best AEP comes from large PV with few batteries: 0.1783 USD/kWh in West and 0.1794 USD/kWh in Central.	Best supplier results come from limited BESS, with annual profit up to 52,503 USD in West and 46,204 USD in Central.	Feasible when battery capacity is small and system sizing is carefully balanced.

6.2. Qualitative considerations and contextual factors

The qualitative results, based on observations during site visits, show that real-world implementation may be a concern, especially for larger PV systems. Although the techno-economic results indicate that solar PV has significant technical and financial potential within the Kenyan tea sector, practical implementation is strongly influenced by qualitative and contextual factors that cannot be fully represented by the calculations alone. These factors include operational reliability, access to financing, organizational know-how and regulatory conditions.

One important aspect identified during the field study period in Kenya was the operational sensitivity of the tea manufacturing process. This concern was both observed during site visits and repeatedly highlighted by interviewees in both the tea- and solar sector ([I3], [I4], [I7]). Tea factories operate continuously during production periods (with the exception of weekly maintenance days) and depend on stable and predictable energy supplies to maintain production efficiency and ensure product quality. Tea leaves are a fresh product that needs processing within a specific time frame from being plucked, and within the correct ambient conditions. Interruptions in power supply may affect several critical process stages, particularly withering and drying, where controlled conditions are necessary. Reliability was therefore identified as a key concern among stakeholders when considering alternative energy systems. However, for a grid-tied PV system to contribute to improved energy security compared to only using the grid, a BESS is needed. This is because any interruptions and power outages on the grid will result in an outage for the PV system as well, as highlighted by the CEO of Miale [I9]. Overall, the analysis indicates that combining a PV system *with* a BESS may improve operational flexibility and increase solar energy utilization. On the other hand, the financial results demonstrate that the addition of battery storage significantly increases capital costs and extends investment payback periods, lowering the overall investment appraisal compared to solar PV systems. As a result, the economic attractiveness of BESS solutions remains limited under current electricity price structures and investment conditions.

This relates to another highly important contextual factor; access to funding and financing. For the outright purchasing financing model, even in the scenarios where financial calculations indicate favorable long-term profitability, the required upfront investment remains a major barrier for many tea factories in Kenya. Investment decision-making typically involve multiple stakeholders and competing financial priorities, particularly within the KTDA management structure. The decision-making process for investment in a solar PV system, particularly one with a BESS backup, is thus largely affected by organizational know-how and stakeholder perceptions on financial priorities. There remains a degree of hesitation regarding new technologies, particularly related to operational reliability, maintenance requirements, and financial risk exposure. Consequently, alternative financing models such as PPA may play an important role in enabling PV energy adaptation, by reducing initial capital requirements and transferring investment risk from the customer to the supplier. The findings indicate that external conditions, such as electricity tariffs and regulatory developments, have a strong influence on the attractiveness of solar PV investment. Uncertainty regarding future tariff structures, tax policies, and Net Metering regulations may create hesitation among investors and factory management, further supporting the attractiveness that risk transfer brings to a PPA setup. Regardless of the financing model, stable and supportive policy frameworks are likely to be important for accelerating solar PV adoption within the tea sector.

7 Discussion

This chapter contains a reflection on what the findings mean in relation to the research questions, industry context, and broader implications.

7.1. Interpretation of results

The results of the Techno-Economic Analysis demonstrate that Solar Photovoltaic (PV) systems have strong potential to reduce electricity costs for tea factories in Kenya, contributing to a sustainable and resilient production system. Across the entire analysis, solar PV is technically and financially attractive, but the preferred energy system setup depends strongly on who owns the system and whether surplus electricity can create value. Overall, there are many factors involved in technical and economic feasibility. System performance, ownership structure, financing model, regulatory conditions and operational priorities are all closely interconnected, and influence whether a project becomes attractive for real-life implementation.

One of the clearest findings from the study is that moderately sized PV systems consistently performed better than oversized systems in the scenarios where Net Metering was assumed unavailable and where a Battery Energy Storage System was not included. This accounts for both customer- and supplier perspective, and for both outright purchase and Power Purchase Agreements (PPA), and highlights an important characteristic of industrial solar PV systems in tea manufacturing; maximizing installed capacity does not necessarily maximize economic value. Since tea factories electricity consumption profile follows a specific operational pattern, there is a limit to how much generated electricity that can be utilized directly within the factory. Solar energy generation is limited to a certain time span across the day, and as Figures 14a and 14b suggests, this time span covers only parts of the operational hours in a tea factory. Increasing system size will not increase this overlap, and once generation exceeds the demand during certain hours of the day, surplus electricity loses value if it cannot be exported to the grid or stored efficiently. The results therefore indicate that system sizing should be based on realistic consumption profiles rather than maximum generation potential. From this perspective, the study demonstrates the importance of integrating technical load analysis with financial optimization when designing and scaling PV systems. Beyond the direct financial aspect, there are practical limitations related to the weight and size of the system that may affect the technical feasibility for the larger systems.

Regulatory conditions, particularly related to the availability of Net Metering, have a strong impact on the overall business case. Across almost all scenarios, the introduction of Net Metering significantly improved financial performance by allowing surplus electricity to create economic value rather than being curtailed. In the strongest customer-owned cases, Net Metering reduced the AEP substantially while also improving NPV, IRR and PP. With a supplier-owned system, introducing Net Metering adds an additional stream of revenue without affecting costs. However, the regulations on system size for Net Metering strongly affect to which degree the financial benefits can be utilized. A larger system generates more excess energy to profit on, and given that the sell price per kWh exceeds the LCOE per kWh, the customer AEP lowers with larger system sizes regardless of financing model. However, since Net Metering is not allowed for larger systems, and since investment costs increase so much with scale, the investment appraisal metrics NPV, IRR and PP still indicate that systems scaled at peak load or lower are more financially viable. This suggests that policy and regulatory structures may be just as important as technological performance in determining the success of solar energy projects. Allowing for Net Metering for larger systems could strengthen the business case of solar PV investment, both for direct outright purchase from the customer and for the supplier with a PPA. As highlighted in section 2.2.2, Kenya has strong renewable energy ambitions that involves private sector participation, and without supportive regulatory incentives, factories may remain limited to smaller systems or dismiss investment altogether. Therefore, the findings puts forward the argument that future expansion of solar PV within the Kenyan industrial sector may depend on how supportive the regulatory environment becomes.

In general, the results indicate a clear difference between the perspectives of the customer and the supplier. For the tea factories, the most important factors are reduced electricity costs and manageable investment requirements. For suppliers such as Miale Solar, profitability depends on project revenue, investment return, and profit margin. Especially under PPA structures, the financial risk and priorities differ vastly between the customer and the supplier. Since the Miale Solar takes on the entire upfront investment as well as the operational costs, and only profits from the billed electricity generated from the system, they depend on strong long-term project economics. To achieve this, they must invest in a system that is favorable in terms of NPV, IRR, PP as well as PM between LCOE and fixed discounted electricity price and potentially Net Metering revenue, as presented in sections 5.6.2 and 6.1.2. The customer on the other hand can simply benefit directly from lower electricity costs directly after installation, and should therefore aim for a system with the lowest possible AEP. The results indicate that the system that is most favorable for the supplier correlates quite well with the one most favorable for the customer. While the customer could benefit from an even larger system, practical barriers could dismiss technical feasibility. The study thus strongly suggests that PPA as a financial model is beneficial for both the customer and supplier, for a scenario both with and without Net Metering.

The outright purchase model is simpler for the supplier perspective. Since they can add a margin on all components sold, they will for sure make a profit on these projects. One important aspect is that outright purchase projects act as a one-time source of income for the supplier, compared to PPA projects that ensure a stable revenue stream over a longer period. However, the upfront investment and thus the investment risk is transferred to the customer. With an outright purchase, AEP is generally lower compared to a PPA. However, while AEP remains higly relevant when comparing different system sizes, NPV, IRR, and PP are now critical for the customer to ensure the investment will create value long-term. The strongest overall customer case identified is an outright purchase of a moderately sized PV system (scale: 0.75-1.25 for both regions) without BESS, both with and without Net Metering, since both AEP and CapEx are relatively low.

Analyzing the role of BESS to complement solar PV is more complex, and the results more difficult to interpret. From a pure economic perspective, BESS generally weakened investment performance as capital costs are high - especially for larger systems where one or two battery replacements are necessary to account for the lifetime of the PV system. Although BESS improved self-consumption and reduced the AEP in many scenarios, these benefits were often outweighed by the additional investment burden. However, BESS holds a practical value that adds an extra parameter to the discussion. During the field study in Kenya and in stakeholder discussions, unreliable grid supply and power outages were repeatedly identified as an operational challenge for tea factories. Since the manufacturing of tea is a continuous and time-sensitive process, interruptions in electricity supply can affect both production efficiency and product quality, and therefor affect the overall output and earnings from finished product. Considering this, BESS may provide strategic value beyond what is reflected in the financial evaluation. This creates a tradeoff between economic optimization and operational resilience. Even if the results indicate that PV systems without BESS produce a stronger business case, systems with small to medium-scaled battery capacity could still be attractive for customers seeking improved energy security and reduced dependence on backup diesel generators. These findings suggest again that optimal system setup depend not only on profitability and pure feasibility, but on strategic and operational priorities.

The economic results party solves the previously raised issue on practical implementation. As mentioned, available area and structural mechanics may preclude installation of some of the larger PV systems. While this issue remains fully case-dependent and is hard to analyse at this point, the best financial scenarios and system setups are smaller and thus more likely to meet the practical requirements.

In terms of sustainability, the results do not provide an adequate analysis of variations between the different scenarios. Also, this assessment focused solely on electrical substitution, excluding the thermal energy that dominates both consumption and emissions in tea manufacturing. Still, replacing grid electricity with renewable generation in Kenyan industries could represent an important step toward more sustainable production. However, the Kenyan electricity mix is already relatively renewable, which could potentially reduce the urgency of private sector solar PV adaptation, compared to countries with fossil-fuel based grids. Regardless, as the results show how economic factors can still motivate the transition to solar PV, reduced pressure on the national grid and a shift towards Kenya's long-term renewable energy ambitions may come as a bonus.

All in all, the results from the study indicate that solar PV in the tea industry is both technically and financially feasible in both Region West and Region Central, but that it is highly sensitive to system size and setup. The best system configuration depends on ownership model, practical barriers and regulatory conditions. The findings thus demonstrate that solar PV for tea manufacturers in Kenya could strengthen long-term competitiveness within the global sector. Electricity costs represent a significant share of production expenses, and electricity tariffs in Kenya remain high and uncertain. By reducing dependence on grid electricity, factories may reduce overall costs, improve cost predictability and avoid exposure to potential tariff increases. However, while the results demonstrate strong feasibility for the medium-sized case factories, implementation at a larger scale may require additional institutional support, technical competence, and financing. For the KTDA managed factories, centralized coordination could potentially create advantages from economy-of-scale and knowledge-sharing, but for the privately owned factories, investment decision making and project management depends fully on the preconception and priorities of the individual factory management.

7.2. Results in relation to research questions

As explained in section 1.3, this thesis aimed to respond to one main research question through addressing three sub-questions. The first sub-question examined which technical and operational factors impact the integration of solar PV systems in tea manufacturing in Kenya. The results indicate that load profile characteristics, system sizing, grid reliability, and operational conditions influence system performance. While all systems assessed in the study were technically feasible and optimized by Delden, findings show that oversized systems can become inefficient if surplus electricity cannot be utilized or exported. Also, operational concerns related to power outages and grid reliability increase the potential value of BESS even if their financial performance is generally weaker, and thus influence technology choices.

The second sub-question aimed to examine the economic viability and potential profitability of installing solar PV systems in Kenyan tea factories. The study demonstates that solar PV systems are financially viable under multiple scenarios, particularily when Net Metering is available so that earnings are generated from excess energy. Customer-owned PV systems with Net Metering provided the strongest customer investment cases with the lowest overall cost of electricity, PPA structures created attractive supplier business cases, especially with Net Metering, with low barriers for factory adaptation and strong financial benefits also for the customer. The results also show that moderate system sizes, scaled at 0.75-1.25 times peak load, generally gives the best balance between electricity cost reduction and investment performance.

The final sub-question focused on external barriers and incentives affecting solar PV adaptation within the Kenyan tea sector. The results indicate that regulatory frameworks strongly affect adoption potential. Especially Net Metering acts as one of the most important incentives by directly adding value to any surplus electricity generated from a system, and as the current regulations restrict implementation, it has a negative influence on the potential for the solar PV business case.

Combined, these findings answer the main research question of the study: how solar PV systems can contribute to a more cost-efficient tea sector in Kenya from a techno-economic perspective. The results show that solar PV systems have a strong potential to reduce electricity cost for tea factories and support the transition towards a more sustainable industrial production. However, the most optimal system setup strongly depends on regulatory conditions, ownership structure, and factory-specific operational and financial priorities.

8 Evaluation

This chapter discusses the results in a broader context. It considers limitations of the study and evaluates the robustness of the findings by analysing reliability, validity, and generalization. Moreover, it contains suggestions for future work on the research topic.

8.1. Limitations of the study

There are certain limitations to this study to point out. One important limitation is that the analysis focuses solely on electrical energy in tea manufacturing. Thermal energy constitutes the largest share of energy consumption in tea manufacturing, so since it was not considered in this analysis, the study does not represent the complete energy transition potential of the tea sector. Electrical energy was prioritized due to the practical relevance of solar PV to subsidize current energy setups, and thus presented a comparatively simple and effective technology to reduce operational costs.

Another limitation concerns the case study object selection. The study is based on KTDA-affiliated tea factories, largely because those were the ones for which data were successfully acquired, and it therefore cannot fully represent the diversity of the entire Kenyan tea sector. Despite the fact that the manufacturing process is nearly identical across the entire sector, factors such as production capacity, local climatic conditions, energy demand patterns, and financial conditions may differ between factories. Consequently, the results should be interpreted as indicative rather than universally representative for all tea manufacturing facilities in Kenya.

As described in section 1.4., the technical optimization and simulation process was carried out by Vilma Delden, and subsequently used as input for the techno-economic assessment. The solar PV systems used in this assessment were thus not developed directly within this thesis but were instead based on simulations and design work conducted externally. While this enabled the study to focus more deeply on the techno-economic and strategic dimensions of solar PV adoption, it also introduced a dependency on external assumptions and modeling decisions that could not be independently verified within the scope of this research. In addition, several assumptions and simplifications were required to perform financial calculations and scenario comparisons. This included e.g., system CapEx, component lifetime, degradation rate, and future electricity tariffs. Although all assumptions were made based on stakeholder insights, supplier data, and current market conditions, future developments may cause significant variations due to inflation, currency fluctuations, policy changes, or technological advancements. Moreover, the diesel consumption was simply added on top of the full electrical energy consumption, since the simulated energy split could not account for power outages and the use of the backup generator. This introduces uncertainty into the long-term economic results, particularly regarding investment appraisal and profitability indicators such as NPV, IRR, and payback period, but also regarding the potential cost reductions and total cost of energy for tea factories.

Finally, the study mainly evaluates solar PV feasibility from a techno-economic perspective, excluding the environmental impacts of different scenarios. Although sustainability aspects are discussed qualitatively, environmental impacts such as embodied emissions, waste management, and lifecycle impacts of batteries and PV components were not quantified.

8.2. Reliability and validity

The reliability of this study was strengthened through the use of multiple data sources and methodological approaches, where quantitative data from simulations, load profiles, technical specifications, and financial calculations were combined with qualitative insights from interviews, field observations, and public sector documentation. This triangulation reduced the dependence on a single source of information and improved the consistency of the findings. The methodological approach, assumptions and calculation methods are carefully described to ensure transparency and reproducibility. Well recognized techno-economic metrics such as LCOE, NPV, IRR, and payback period were applied in the analysis, using established theoretical frameworks and equations. This further contributes to methodological reliability and allows future studies to replicate or further develop the analysis. On the other hand, reliability may be weakened by subjective interpretations and bias, as several interview responses reflected stakeholder perceptions and expectations regarding solar PV adoption, financing, and operational challenges. Additionally, the availability and quality of operational factory data varied between cases, where average values have been used instead of factory-specific data. This may have influenced the precision of some calculations and comparisons between scenarios.

The validity of the study was strengthened by aligning the chosen frameworks and methodology closely with the research topic and the research questions. By combining qualitative field insights and quantitative analysis, both techno-economic feasibility and contextual incentives and barriers could be evaluated together. At the same time, external validity remains limited due to the case-specific nature of the study. The findings are applicable to tea factories in Kenya that operate under similar conditions as the case factories, which should be cautioned when applying conclusions to other industrial or geographical contexts.

8.3. Generalization

Although this study is based on a limited number of case factories, only including about half of the total in Kenya and none that are privately owned and managed, several findings may still be transferable across the entire sector in Kenya and other regions in East Africa. It could even apply to similar agro-industrial sectors with similar operational schedules and load profiles. The regulatory frameworks, electricity tariffs and operational requirements influencing the tea manufacturing process is not unique to that particular sector, and could be relevant across multiple industries such as coffee processing, food manufacturing and horticulture. While specific results on technical and financial feasibility identified in this study depend heavily on local conditions and should primarily be viewed as context-dependent rather than universally generalizable, the methodology for optimization is the same regardless of context and the framework can easily be applied across a broader range of industries and geographic locations.

8.4. Future work

While the results of this study properly respond to the research questions, certain aspects remain open for further research due to time constraints and data limitations. One important area for future work is a more targeted sensitivity analysis of the financial model developed in this study. The scenarios assessed are based solely on medium-sized factories and on fixed assumptions or generalized values e.g., electricity tariffs and capital costs, and these parameters are subject to considerable uncertainty in real-life projects and the Kenyan context. As mentioned in section 2.2.2, Kenya's strategy and vision for development of the energy market is uncertain and there are several different potential scenarios in their forecast. Future work could explore how changes in grid tariff trajectories, fuel price fluctuation and development of PV and BESS component costs affect the financial viability of different system configurations and scenarios. Additionally, since this study relied on a single representative load profile scaled across average values for medium-sized factories, future research could benefit from incorporating measured hourly load data from a broader set of factories, including small-scale and large-scale, as well as seasonal variations.

Future studies could also expand the analysis to include thermal energy substitution within tea manufacturing. Since thermal processes account for a substantial share of total energy consumption in tea factories and since the current source is firewood, optimizing consumption or integrating new technologies such as solar thermal systems or hybrid renewable energy systems could provide a more complete understanding of decarbonization and cost-saving opportunities within the sector. Moreover, it would be interesting to explore the impact of solar integration for energy substitution in the whole value chain of tea in Kenya. Since this study focuses solely on the manufacturing process in tea factories, it leaves out the farming and the transportation of green leaves to factories and of finished tea to the Mombasa Tea Auction. As nearly all Kenyan tea is sold through the Mombasa tea auction, located in Mombasa at the coast, and as most Kenyan tea farms and factories are located in the central or western regions of the country, transport is not a negligible part of energy consumption. Future studies could thus explore the possibility of substituting current transportation means to electric vehicles fueled by solar power, to minimize carbon emissions related to the tea sector.

Another relevant area for future research is a full life cycle assessment (LCA) of the energy systems evaluated in the study. While this analysis demonstrated clear financial benefits for several system configurations, it does not capture the environmental footprint associated with the system life cycle. Given that the systems modeled include multiple components, some of which require replacements within the assessed timeframe, the cumulative environmental cost of raw materials, manufacturing, transportation, operation and end-of-life could be substantial. Given that Kenya's national grid mainly provides energy from renewable sources, as mentioned in section 2.2, transitioning to private PV systems like the ones modeled in this study may not be the best solution from a sustainability perspective. An LCA would provide a more complete picture of the sustainability credentials of solar PV in Kenyan tea manufacturing, and would be particularly valuable for factories or financiers seeking to document environmental performance for carbon credit schemes or ESG reporting purposes. It would also align with the Tea Board of Kenya's (TBK) 2023-2027 Strategic Plan, which highlights the need to address sustainability and climate change challenges in the tea sector.

Lastly, future studies could explore the impact of evolving regulatory frameworks, carbon financing mechanisms, and innovative financing models such as green bonds or blended finance structures. These factors may significantly influence the future of solar PV systems within Kenya's tea sector.

9 Conclusion

This thesis has assessed how solar PV systems can contribute to a more cost-efficient tea production in Kenya from a techno-economic perspective. Based on the technical, financial and contextual findings, this study concludes that solar PV is both technically feasible and economically attractive for tea factories. This was particularly found for PV systems carefully sized according to factory load profiles and operational conditions. Since electricity is a major cost driver for factories, substituting it with solar PV is a relevant strategy for reducing costs and improving long-term cost predictability.

Regarding the first sub question, sections 5.2 and 6.1.1 show that the main technical and operational factors affecting solar PV integration are factory load profiles, system size, solar resource, available area for installation, and the ability to utilize surplus generated electricity. The results also show that PV systems are technically feasible for all medium-sized assessed factories, but also that larger systems are not always more suitable. If excess electricity cannot be exported, stored or directly consumed, the large-scale systems are less efficient. As discussed in sections 5.3.1 and 6.1.1, BESS can store surplus electricity, thereby improving operational reliability. Still, their cost, size, weight and replacement needs create additional practical and financial challenges.

The second sub question focused on economic viability and profitability. The financial results in section 6.1.2 show that solar PV can reduce the average electricity price and create profitable investment cases in several scenarios. In general, outright purchase systems with Net Metering and without BESS provided the strongest financial outcome for the factories. The strongest financial results were generally found for systems around 0.75 to 1.0 times the factory peak load. The PPA model was also found to be financially attractive, as it allows factories to reduce electricity costs without upfront investment, while offering the supplier strong profit potential when sufficient electricity is sold to the factory. The BESS scenario improved the use of solar electricity and reduced grid dependence, but was less financially attractive due to higher investment costs.

The third sub question addressed external barriers and incentives. The findings in section 5.3 indicate that the most important incentive is Net Metering, since it allows surplus electricity to create value instead of being curtailed. However, limits regarding peak load scaling and maximum capacity reduce the potential benefit for larger systems. Other barriers include upfront costs, regulatory uncertainty, technical skill requirements, site specific constraints and the need for long term agreements.

Overall, the main research question can be answered by concluding that solar PV systems, both with and without BESS, can contribute to more cost-efficient tea production in Kenya by lowering electricity costs, improving long term price stability and improving reliability when BESS is included. However, the most suitable system setup depends on system size, factory demand, ownership model, financing structure, regulatory conditions and power reliability priorities.

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Appendix

9.1. MATLAB Codes

Base Case

```
clc;
clear all;

filename = '';
data = readtable(filename);

load_profile = data.Load;
E_load =  sum(load_profile) ;

%% =======================
% --- Prices ---
% =======================

grid_price = 0.21;

%% =======================
% --- Diesel
% =======================
fuel_usage        = X;          % L/year
fuel_price        = 1.3167;            % USD/L
diesel_efficiency = 3;                 % kWh/L
E_diesel          = fuel_usage * diesel_efficiency;
diesel_price      = fuel_price / diesel_efficiency;   % USD/kWh

%% =======================
% --- Total cost & AEP ---
% =======================

total_op_cost = E_load * grid_price  + E_diesel*diesel_price;

average_price = total_op_cost / (E_load + E_diesel);
fprintf('Average electricity price: %.6f USD/kWh\n', average_price);
```

Grid-tied PV system without BESS

```
filename = '';
data = readtable(filename);

load_profile = data.Load;
pv_to_load   = data.PV_L;
pv_to_grid = data.PV_G;
grid_to_load = data.G_L;

%% =======================
% --- Energy split (from SAM)
% =======================

E_pv_direct = sum(pv_to_load);
E_grid      = sum(grid_to_load);
E_export    = sum(pv_to_grid);   % 0 for the _C (curtailed) files
E_load      = sum(load_profile);


%% =======================
% PV PARAMETERS
% =======================

pv_annual_energy =  E_pv_direct + E_export; % kWh/year
sys_size = X;
sys_capex = X; % USD per kW

pv_capex = sys_capex * sys_size;    % USD initial investment

pv_om = sys_size*7.5;  %USD / year, alt: 7,5 USD/kW as given by Miale

pv_lifetime = 25;         % years
discount_rate = 0.11;

%% =======================
% LCOE CALCULATION
% =======================
total_cost = pv_capex;
total_energy = 0;
degradation_rate = 0.005;

for y = 1:pv_lifetime
```

```
    df = 1 / (1 + discount_rate)^y;

    yearly_cost = pv_om;
    yearly_energy = pv_annual_energy*(1 - degradation_rate)^(y-1);;

    total_cost = total_cost + yearly_cost * df;
    total_energy = total_energy + yearly_energy * df;
end

LCOE_pv = total_cost / total_energy;

fprintf('PV LCOE: %.6f USD/kWh\n', LCOE_pv);

%% =======================
% --- Diesel
% =======================
fuel_usage        = X;          % L/year
fuel_price        = 1.3167;            % USD/L
diesel_efficiency = 3;                 % kWh/L
E_diesel          = fuel_usage * diesel_efficiency;
diesel_price      = fuel_price / diesel_efficiency;   % USD/kWh

%% =======================
% --- Prices ---
% =======================

grid_price = 0.21;
sell_price = grid_price/2;   % set to 0 for no-net-metering case

%% =======================
% --- Total cost & AEP ---
% =======================

total_op_cost = pv_annual_energy*LCOE_pv ...
              + E_grid*grid_price ...
              + E_diesel*diesel_price ...
              - E_export*sell_price;

average_price = total_op_cost / (E_load + E_diesel);
fprintf('Average electricity price: %.6f USD/kWh\n', average_price);
```

Grid-tied PV system with BESS

```
clc;
clear;

filename = '';
data = readtable(filename);

load_profile = data.Load
pv_to_battery   = data.PV_B;
battery_to_load = data.B_L;
pv_to_load      = data.PV_L;
grid_to_load    = data.G_L;

%% =======================
% PV PARAMETERS
% =======================
pv_lifetime      = 25;       % years
discount_rate    = 0.11;
degradation_rate = 0.005;    % PV panel degradation rate per year
grid_price       = 0.21;     % USD/kWh

sys_size      = X;       % kWp DC
sys_capex     = X;   % USD/kW

%% =======================
% DIESEL PARAMETERS
% =======================
fuel_usage       = X * 0.1;    % L/year
fuel_price       = 1.3167;    % USD/L
diesel_efficiency = 3;       % kWh/L
E_diesel          = fuel_usage * diesel_efficiency;
diesel_price      = fuel_price / diesel_efficiency;

 %% =======================
% BESS PARAMETERS
% =======================

batt_modules   = X;
capacity_kwh   = 233;         % kWh per module
storage_capex = 220;   % USD/kWh
cycles_per_year = 365;
```

```
efficiency      = 1;         % round-trip efficiency (accounted for in SAM)

%% ======================
% ENERGY SPLIT
% ======================
E_pv_direct = sum(pv_to_load);
E_batt_in   = sum(pv_to_battery);
E_batt_out  = sum(battery_to_load);
E_grid      = sum(grid_to_load);
E_load      = sum(load_profile);

%% ======================
% BATTERY REPLACEMENT DETECTION
% ======================
batt_deg_col   = data{:,5};
initial_cap_ah = batt_deg_col(1);
sim_years      = numel(batt_deg_col) / (24 * 365);

jumps = find(diff(batt_deg_col) > 50);
num_replacements   = length(jumps);
batt_replacement_year  = NaN;
batt_replacement_year2 = NaN;

if num_replacements == 0
    % No replacement needed within project lifetime

elseif num_replacements == 1
    batt_replacement_year = floor(jumps(1) / (24*365));

else
    batt_replacement_year = floor(jumps(1) / (24*365));
    second_reset_year = jumps(2) / (24*365);
    if second_reset_year < pv_lifetime - 1
        batt_replacement_year2 = floor(jumps(2) / (24*365));
    else
        num_replacements = 1;   % late replacement ignored
    end
end

%% ======================
% DERIVED QUANTITIES
```

```
% ========================
pv_annual_energy = (E_pv_direct + E_batt_in) / pv_lifetime;
pv_capex         = sys_capex * sys_size;
pv_om            = sys_size * 7.5;
batt_capacity    = batt_modules * capacity_kwh;
batt_capex       = storage_capex * batt_capacity;
batt_om          = batt_capacity * 5;
annual_discharge = batt_capacity * cycles_per_year * efficiency;
E_pv_batt_annual = (E_pv_direct + E_batt_out) / pv_lifetime;

%% ========================
% PV LCOE
% ========================
total_cost_pv = pv_capex;
total_energy_pv = 0;
for y = 1:pv_lifetime
    df = 1 / (1 + discount_rate)^y;
    total_cost_pv   = total_cost_pv   + pv_om * df;
    total_energy_pv = total_energy_pv + pv_annual_energy * (1 - degradation_rate)^(y-1) * df;
end
LCOE_pv = total_cost_pv / total_energy_pv;

%% ========================
% LCOS
% ========================
total_cost_batt   = batt_capex;
total_energy_batt = 0;
for y = 1:pv_lifetime
    df = 1 / (1 + discount_rate)^y;
    yc = batt_om;
    if num_replacements >= 1 && ~isnan(batt_replacement_year) && y == batt_replacement_year + 1
        yc = yc + batt_capex;
    end
    if num_replacements >= 2 && ~isnan(batt_replacement_year2) && y == batt_replacement_year2 + 1
        yc = yc + batt_capex;
    end
    total_cost_batt   = total_cost_batt   + yc * df;
    total_energy_batt = total_energy_batt + annual_discharge * df;
end
```

```
LCOS_batt = total_cost_batt / total_energy_batt;
cost_batt_delivered = LCOE_pv / efficiency + LCOS_batt;

%% =======================
% SYSTEM LCOE (PV + Battery)
% =======================
total_cost_sys   = pv_capex + batt_capex;
total_energy_sys = 0;
for y = 1:pv_lifetime
    df = 1 / (1 + discount_rate)^y;
    yc = pv_om + batt_om;
    if num_replacements >= 1 && ~isnan(batt_replacement_year) && y ==
        batt_replacement_year + 1
        yc = yc + batt_capex;
    end
    if num_replacements >= 2 && ~isnan(batt_replacement_year2) && y ==
        batt_replacement_year2 + 1
        yc = yc + batt_capex;
    end
    total_cost_sys   = total_cost_sys   + yc * df;
    total_energy_sys = total_energy_sys + E_pv_batt_annual * (1 -
        degradation_rate)^(y-1) * df;
end
LCOE_system = total_cost_sys / total_energy_sys;

%% =======================
% AVERAGE ELECTRICITY COST
% =======================
total_cost_avg = ...
    E_pv_direct * LCOE_pv + ...
    E_batt_out  * cost_batt_delivered + ...
    E_grid      * grid_price + ...
    E_diesel    * diesel_price;
average_price = total_cost_avg / E_load;

%% =======================
% RESULTS
% =======================
fprintf('PV LCOE:                   %.4f USD/kWh\n', LCOE_pv);
fprintf('Battery LCOS:              %.4f USD/kWh\n', LCOS_batt);
fprintf('System LCOE (PV+Battery):  %.4f USD/kWh\n', LCOE_system);
fprintf('Average electricity price: %.4f USD/kWh\n', average_price);
```

PV system without BESS - PPA calculations

```
clc;
clear;

filename = '';
data = readtable(filename);

load_profile = data.Load;
pv_to_load   = data.PV_L;
pv_to_grid = data.PV_G;
grid_to_load = data.G_L;

%% =======================
% --- Energy split (from SAM)
% =======================

E_pv_direct = sum(pv_to_load);
E_grid      = sum(grid_to_load);
E_export    = sum(pv_to_grid);
E_load      = sum(load_profile);

%% =======================
% --- Prices ---
% =======================

grid_price = 0.21;
sell_price = grid_price/2;
discounted_price_pv = grid_price*0.6;

%% =======================
% PV PARAMETERS
% =======================

pv_annual_energy =  E_pv_direct + E_export; % kWh/year (after curtailment
    if applicable)
sys_size = X;
sys_capex = X; % USD per kW

pv_capex = sys_capex * sys_size;    % USD initial investment
```

```
pv_om = sys_size*7.5;  %USD / year, alt: 7,5 USD/kW as given by Miale

pv_lifetime = 25;          % years
discount_rate = 0.11;

%% =======================
% LCOE CALCULATION
% =======================
total_cost = pv_capex;
total_energy = 0;
degradation_rate = 0.005;

for y = 1:pv_lifetime
    df = 1 / (1 + discount_rate)^y;

    yearly_cost = pv_om;
    yearly_energy = pv_annual_energy*(1 - degradation_rate)^(y-1);;

    total_cost = total_cost + yearly_cost * df;
    total_energy = total_energy + yearly_energy * df;
end

LCOE_pv = total_cost / total_energy;

fprintf('PV LCOE: %.6f USD/kWh\n', LCOE_pv);

%% =======================
% --- Diesel
% =======================
fuel_usage         = X;           % L/year
fuel_price         = 1.3167;             % USD/L
diesel_efficiency = 3;                   % kWh/L
E_diesel           = fuel_usage * diesel_efficiency;
diesel_price       = fuel_price / diesel_efficiency;   % USD/kWh

%% =======================
% --- Total cost & AEP ---
% =======================

total_op_cost = E_pv_direct*discounted_price_pv ...
              + E_grid*grid_price ...
```

```
                + E_diesel*diesel_price;

NM_annual_profit =  E_export*sell_price;

average_price = total_op_cost / (E_load + E_diesel);
fprintf('Average electricity price: %.6f USD/kWh\n', average_price);
fprintf('Potential NM profit: %.0f USD/kWh\n', NM_annual_profit);
```

PV system with BESS - PPA calculations

```
clc;
clear;

filename = '';

data = readtable(filename);
load_profile    = data.Load;
pv_to_battery   = data.PV_B;
battery_to_load = data.B_L;
pv_to_load      = data.PV_L;
grid_to_load    = data.G_L;

%% =======================
% BATTERY DEGRADATION & REPLACEMENT DETECTION
% =======================
batt_deg_col   = data{:,5};
initial_cap_ah = batt_deg_col(1);
sim_years      = numel(batt_deg_col) / (24 * 365);   % = 25

jumps = find(diff(batt_deg_col) > 50);
num_replacements = length(jumps);
fprintf('SAM battery replacements detected: %d\n', num_replacements);
for i = 1:num_replacements
    fprintf('  Replacement %d at year %.1f\n', i, jumps(i)/(24*365));
end

if num_replacements == 0
    final_cap_ah  = batt_deg_col(end);
    batt_deg_rate = (initial_cap_ah - final_cap_ah) / initial_cap_ah /
        sim_years;
```

```
    fprintf('No replacement detected. Deg rate: %.4f%%/year\n', batt_deg_rate*100);
    batt_replacement_year  = NaN;
    batt_replacement_year2 = NaN;

elseif num_replacements == 1
    first_reset_hour = jumps(1);
    first_reset_year = first_reset_hour / (24 * 365);
    cap_at_reset     = batt_deg_col(first_reset_hour);
    batt_deg_rate    = (initial_cap_ah - cap_at_reset) / initial_cap_ah / first_reset_year;
    fprintf('First battery replaced at year %.1f (%.1f%% SOH)\n', ...
        first_reset_year, cap_at_reset/initial_cap_ah*100);
    fprintf('Battery annual degradation rate: %.4f%%/year\n', batt_deg_rate*100);
    batt_replacement_year  = floor(jumps(1) / (24*365));
    batt_replacement_year2 = NaN;
    fprintf('CAPEX replacement at year %d.\n', batt_replacement_year+1);

else
    first_reset_hour = jumps(1);
    first_reset_year = first_reset_hour / (24 * 365);
    cap_at_reset     = batt_deg_col(first_reset_hour);
    batt_deg_rate    = (initial_cap_ah - cap_at_reset) / initial_cap_ah / first_reset_year;
    fprintf('First battery replaced at year %.1f (%.1f%% SOH)\n', ...
        first_reset_year, cap_at_reset/initial_cap_ah*100);
    fprintf('Battery annual degradation rate: %.4f%%/year\n', batt_deg_rate*100);
    batt_replacement_year = floor(jumps(1) / (24*365));

    second_reset_year = jumps(2) / (24*365);
    if second_reset_year < sim_years - 1
        batt_replacement_year2 = floor(jumps(2) / (24*365));
        num_replacements = 2;
        fprintf('CAPEX replacements at years %d and %d.\n', ...
            batt_replacement_year+1, batt_replacement_year2+1);
    else
        batt_replacement_year2 = NaN;
        num_replacements = 1;
        fprintf('Second replacement at year %.2f ignored (too close to end of lifetime).\n', ...
```

```
            second_reset_year);
        fprintf('CAPEX replacement at year %d only.\n',
           batt_replacement_year+1);
    end
end

%% =======================
% DIESEL
% =======================
% PPA scenario: diesel reduced to 10% of baseline (battery present)
fuel_usage        = X * 0.1;   % L/year
fuel_price        = 1.3167;          % USD/L
diesel_efficiency = 3;               % kWh/L
E_diesel          = fuel_usage * diesel_efficiency;
diesel_price      = fuel_price / diesel_efficiency;   % USD/kWh

%% =======================
% ENERGY SPLIT (25-year simulation totals)
% =======================
E_pv_direct = sum(pv_to_load);
E_batt_in   = sum(pv_to_battery);
E_batt_out  = sum(battery_to_load);
E_grid      = sum(grid_to_load);
E_load      = sum(load_profile);

%% =======================
% PV PARAMETERS
% =======================
pv_lifetime      = 25;       % years
discount_rate    = 0.11;
degradation_rate = 0.005;    % 0.5%/year PV panel degradation

pv_annual_energy = (E_pv_direct + E_batt_in) / pv_lifetime;

sys_size  = X;     % kWp DC
sys_capex = X;       % USD/kW
pv_capex  = sys_capex * sys_size;
pv_om     = sys_size * 7.5;    % USD/year

%% =======================
% PPA PRICE
% =======================
```

```
grid_price = 0.21;              % USD/kWh
ppa_price  = grid_price * 0.6; % USD/kWh

%% =======================
% PV LCOE CALCULATION
% =======================
total_cost_pv    = pv_capex;
total_energy_pv = 0;

for y = 1:pv_lifetime
    df              = 1 / (1 + discount_rate)^y;
    yearly_energy = pv_annual_energy * (1 - degradation_rate)^(y-1);
    total_cost_pv    = total_cost_pv    + pv_om * df;
    total_energy_pv = total_energy_pv + yearly_energy * df;
end

LCOE_pv = total_cost_pv / total_energy_pv;
fprintf('PV LCOE: %.4f USD/kWh\n', LCOE_pv);

%% =======================
% BATTERY PARAMETERS
% =======================
cycles_per_year = 365;
capacity_kwh     = 233;       % kWh per module
efficiency       = 1;         % already accounted for in SAM simulation

batt_modules   = X;           % update per scenario
batt_capacity = batt_modules * capacity_kwh;

storage_capex = 220;         % USD/kWh      1x capex only for PPA scenario
batt_capex     = storage_capex * batt_capacity;
batt_om        = batt_capacity * 5;    % USD/year (5 USD/kWh of total
    capacity)

%% =======================
% ENERGY THROUGHPUT
% =======================
annual_discharge = batt_capacity * cycles_per_year * efficiency;

%% =======================
% LCOS CALCULATION
% =======================
```

```
total_cost_batt   = batt_capex;
total_energy_batt = 0;

for y = 1:pv_lifetime
    df          = 1 / (1 + discount_rate)^y;
    yearly_cost = batt_om;

    if num_replacements >= 1 && ~isnan(batt_replacement_year)
        if y == batt_replacement_year + 1
            yearly_cost = yearly_cost + batt_capex;
            fprintf('  -> Replacement 1 CAPEX added at year %d (discounted).\n', y);
        end
    end
    if num_replacements >= 2 && ~isnan(batt_replacement_year2)
        if y == batt_replacement_year2 + 1
            yearly_cost = yearly_cost + batt_capex;
            fprintf('  -> Replacement 2 CAPEX added at year %d (discounted).\n', y);
        end
    end

    total_cost_batt   = total_cost_batt   + yearly_cost * df;
    total_energy_batt = total_energy_batt + annual_discharge * df;
end

LCOS_batt = total_cost_batt / total_energy_batt;
fprintf('Battery LCOS (storage only): %.4f USD/kWh\n', LCOS_batt);

% In the PPA scenario, the charging cost uses the PPA price
% (not LCOE_pv) since the factory pays the PPA rate for all PV energy
cost_batt_delivered = ppa_price + LCOS_batt;

%% ======================
% SYSTEM LCOE (PV + Battery combined)
% ======================
% Denominator: energy delivered to load by PV+battery (no double counting)
E_pv_batt_annual = (E_pv_direct + E_batt_out) / pv_lifetime;

total_cost_sys    = pv_capex + batt_capex;
total_energy_sys = 0;

```

```
for y = 1:pv_lifetime
    df          = 1 / (1 + discount_rate)^y;
    yearly_cost = pv_om + batt_om;

    if num_replacements >= 1 && ~isnan(batt_replacement_year)
        if y == batt_replacement_year + 1
            yearly_cost = yearly_cost + batt_capex;
        end
    end
    if num_replacements >= 2 && ~isnan(batt_replacement_year2)
        if y == batt_replacement_year2 + 1
            yearly_cost = yearly_cost + batt_capex;
        end
    end

    yearly_energy    = E_pv_batt_annual * (1 - degradation_rate)^(y-1);
    total_cost_sys   = total_cost_sys   + yearly_cost * df;
    total_energy_sys = total_energy_sys + yearly_energy * df;
end

LCOE_system = total_cost_sys / total_energy_sys;
fprintf('System LCOE (PV + Battery): %.4f USD/kWh\n', LCOE_system);

%% =======================
% AVERAGE ELECTRICITY COST (factory perspective)
% =======================
% PV direct and battery output priced at PPA rate
% Grid at grid price, diesel at diesel price
E_pv_direct_ann = E_pv_direct / pv_lifetime;
E_batt_out_ann  = E_batt_out  / pv_lifetime;
E_grid_ann      = E_grid      / pv_lifetime;

total_cost_avg = ...
    E_pv_direct_ann * ppa_price + ...
    E_batt_out_ann  * cost_batt_delivered + ...
    E_grid_ann      * grid_price + ...
    E_diesel        * diesel_price;

average_price = total_cost_avg / (E_pv_direct_ann + E_batt_out_ann + E_grid_ann + E_diesel);

%% =======================
```

```
% MIALE PROFIT MARGIN & ANNUAL PROFIT
% =======================

profit_margin = (ppa_price - LCOE_system) / ppa_price;
annual_profit = (ppa_price - LCOE_system) * E_pv_batt_annual;

%% =======================
% CAPEX SUMMARY
% =======================
fprintf('\nYear-0 batt CAPEX: %.0f USD\n', batt_capex);
if num_replacements == 0
    fprintf('No battery replacement needed within 25 years.\n');
elseif num_replacements == 1
    fprintf('Replacement 1 CAPEX (yr %d): %.0f USD (discounted: %.0f
       USD)\n', ...
        batt_replacement_year+1, batt_capex, ...
        batt_capex/(1+discount_rate)^(batt_replacement_year+1));
else
    fprintf('Replacement 1 CAPEX (yr %d): %.0f USD (discounted: %.0f
       USD)\n', ...
        batt_replacement_year+1, batt_capex, ...
        batt_capex/(1+discount_rate)^(batt_replacement_year+1));
    fprintf('Replacement 2 CAPEX (yr %d): %.0f USD (discounted: %.0f
       USD)\n', ...
        batt_replacement_year2+1, batt_capex, ...
        batt_capex/(1+discount_rate)^(batt_replacement_year2+1));
end

if length(jumps) >= 2
    second_reset_year = jumps(2) / (24*365);
    if second_reset_year >= pv_lifetime - 1
        fprintf('\nNote: SAM detected a second replacement at year
           %.2f,\n', second_reset_year);
        fprintf('but it was ignored as it falls within the last year of
           the project lifetime.\n');
    end
end

%% =======================
% SUMMARY
% =======================
fprintf('\n--- SUMMARY ---\n');
```

```
fprintf('PV LCOE:                       %.4f USD/kWh\n', LCOE_pv);
fprintf('Battery LCOS:                  %.4f USD/kWh\n', LCOS_batt);
fprintf('System LCOE (PV+Batt):         %.4f USD/kWh\n', LCOE_system);
fprintf('\n-- Factory perspective --\n');
fprintf('Average electricity price: %.4f USD/kWh\n', average_price);
fprintf('\n-- Miale (supplier) perspective --\n');
fprintf('Profit margin:                 %.1f%%\n', profit_margin * 100);
fprintf('Annual profit:                 %.0f USD/year\n', annual_profit);
```

Investment appraisal calculations - PV without BESS

```
clc; clear;
format longg

filename = '';
data = readtable(filename);

load_profile = data.Load
pv_to_load   = data.PV_L;
pv_to_grid   = data.PV_G;
grid_to_load = data.G_L;

%% =======================
% PARAMETERS
% =======================
pv_lifetime       = 25;       % years
discount_rate     = 0.11;
degradation_rate  = 0.005;    %
grid_price        = 0.21;     % USD/kWh
sell_price        = grid price/2;        % USD/kWh (set to 0 for no net
   metering)
fuel_usage        = X;        % L/year
fuel_price        = 1.3167;   % USD/L
diesel_efficiency = 3;        % kWh/L
diesel_price      = fuel_price / diesel_efficiency;

sys_size  = 800.8;            % kWp DC
sys_capex = 400;              % USD/kW (1x capex; use 400*1.3 for 1.3x)

%% =======================
% ENERGY SPLIT (annual, from 1-year SAM simulation)
```

```
% =======================
E_pv_direct = sum(pv_to_load);   % kWh/year
E_export    = sum(pv_to_grid);   % kWh/year
E_grid      = sum(grid_to_load); % kWh/year
E_elec_ann  = sum(load_profile);   % annual electrical load

E_diesel = fuel_usage * diesel_efficiency;   % kWh/year

%% =======================
% DERIVED QUANTITIES
% =======================
pv_annual_energy = E_pv_direct + E_export;
pv_capex         = sys_capex * sys_size;
pv_om            = sys_size * 7.5;

%% =======================
% PV LCOE
% =======================
total_cost_pv = pv_capex; total_energy_pv = 0;
for y = 1:pv_lifetime
    df = 1 / (1 + discount_rate)^y;
    total_cost_pv   = total_cost_pv   + pv_om * df;
    total_energy_pv = total_energy_pv + pv_annual_energy * (1 -
        degradation_rate)^(y-1) * df;
end
LCOE_pv = total_cost_pv / total_energy_pv;

%% =======================
% BASELINE ANNUAL COST (no system)
% =======================
baseline_annual = E_elec_ann * grid_price + E_diesel * diesel_price;

%% =======================
% NPV / IRR / PAYBACK PERIOD
% =======================
cash_flows    = zeros(1, pv_lifetime + 1);
cash_flows(1) = -pv_capex;   % year 0: initial investment

for y = 1:pv_lifetime
    deg = (1 - degradation_rate)^(y-1);
    pv_gen_y = pv_annual_energy * deg;

```

```
    % Annual system operating cost (PV energy at LCOE, grid remainder,
       diesel unchanged)
    sys_cost_y = pv_gen_y * LCOE_pv ...
               + E_grid * grid_price ...
               + E_diesel * diesel_price ...
               - E_export * sell_price * deg ...
               + pv_om;

    cash_flows(y+1) = baseline_annual - sys_cost_y;
end

% NPV
t   = 0:pv_lifetime;
NPV = sum(cash_flows ./ (1 + discount_rate).^t);

% IRR (bisection)
f   = @(r) sum(cash_flows ./ (1 + r).^t);
lo  = -0.5; hi = 5.0;
for k = 1:200
    mid = (lo + hi) / 2;
    if f(mid) > 0; lo = mid; else; hi = mid; end
end
IRR = (lo + hi) / 2;

% Simple payback period (undiscounted cumulative cash flows)
cumulative = cumsum(cash_flows);
pp_idx     = find(cumulative >= 0, 1);
if isempty(pp_idx)
    PP = Inf;
else
    PP = pp_idx - 1;
end

%% ======================
% RESULTS
% ======================
fprintf('--- LCOE ---\n');
fprintf('PV LCOE:                   %.4f USD/kWh\n', LCOE_pv);
fprintf('\n--- Investment Metrics ---\n');
fprintf('Total CapEx:               %.0f USD\n',    pv_capex);
fprintf('Baseline annual cost:      %.0f USD/yr\n', baseline_annual);
fprintf('Year 1 savings:            %.0f USD\n',    cash_flows(2));
```

```
fprintf('NPV:                          %.0f USD\n',    NPV);
fprintf('IRR:                          %.2f%%\n',      IRR * 100);
fprintf('Simple payback period:     %d years\n',    PP);
```

Investment appraisal calculations - PV with BESS

```
clc; clear;
format longg

filename = '';
data = readtable(filename);

load_profile = data.Load;
pv_to_battery   = data.PV_B;
battery_to_load = data.B_L;
pv_to_load      = data.PV_L;
grid_to_load    = data.G_L;

%% ======================
% PV, Diesel & Battery PARAMETERS
% ======================
pv_lifetime       = 25;       % years
discount_rate     = 0.11;
degradation_rate  = 0.005;    % PV panel degradation rate per year
grid_price        = 0.21;     % USD/kWh
fuel_usage        = X; % L/year baseline, no battery (use 15625.83 for
   West)
fuel_price        = 1.3167;   % USD/L
diesel_efficiency = 3;        % kWh/L
diesel_price      = fuel_price / diesel_efficiency;

sys_size        = X;      % kWp DC
sys_capex       = X;        % USD/kW (1x capex)
batt_modules    = X;
capacity_kwh    = 233;        % kWh per module
storage_capex   = 220;        % USD/kWh (1x capex)
cycles_per_year = 365;
efficiency      = 1;          % round-trip efficiency (accounted for in
   SAM)

%% ======================
```

```
% ENERGY SPLIT (25-year simulation totals)
% ======================
E_pv_direct = sum(pv_to_load);
E_batt_in    = sum(pv_to_battery);
E_batt_out   = sum(battery_to_load);
E_grid       = sum(grid_to_load);
E_load = sum(load_profile);

% Annual averages
E_pv_ann    = E_pv_direct / pv_lifetime;
E_batt_ann = E_batt_out  / pv_lifetime;
E_grid_ann = E_grid      / pv_lifetime;
E_elec_ann = E_load / pv_lifetime;  % annual electrical load

% System diesel (10% of baseline with battery)
E_diesel_sys  = fuel_usage * 0.1 * diesel_efficiency;   % kWh/year

% Baseline diesel (full consumption, no battery)
E_diesel_base = fuel_usage * diesel_efficiency;          % kWh/year

%% ======================
% BATTERY REPLACEMENT DETECTION
% ======================
batt_deg_col    = data{:,5};
initial_cap_ah = batt_deg_col(1);
sim_years       = numel(batt_deg_col) / (24 * 365);

jumps = find(diff(batt_deg_col) > 50);
num_replacements    = length(jumps);
batt_replacement_year   = NaN;
batt_replacement_year2 = NaN;

if num_replacements == 1
    batt_replacement_year = floor(jumps(1) / (24*365));
elseif num_replacements >= 2
    batt_replacement_year = floor(jumps(1) / (24*365));
    second_reset_year = jumps(2) / (24*365);
    if second_reset_year < pv_lifetime - 1
        batt_replacement_year2 = floor(jumps(2) / (24*365));
    else
        num_replacements = 1;
    end
```

```
end

%% ========================
% DERIVED QUANTITIES
% ========================
pv_annual_energy = (E_pv_direct + E_batt_in) / pv_lifetime;
pv_capex         = sys_capex * sys_size;
pv_om            = sys_size * 7.5;
batt_capacity    = batt_modules * capacity_kwh;
batt_capex       = storage_capex * batt_capacity;
batt_om          = batt_capacity * 5;
annual_discharge = batt_capacity * cycles_per_year * efficiency;
E_pv_batt_annual = (E_pv_direct + E_batt_out) / pv_lifetime;

%% ========================
% PV LCOE
% ========================
total_cost_pv = pv_capex; total_energy_pv = 0;
for y = 1:pv_lifetime
    df = 1 / (1 + discount_rate)^y;
    total_cost_pv   = total_cost_pv   + pv_om * df;
    total_energy_pv = total_energy_pv + pv_annual_energy * (1 -
       degradation_rate)^(y-1) * df;
end
LCOE_pv = total_cost_pv / total_energy_pv;

%% ========================
% LCOS
% ========================
total_cost_batt = batt_capex; total_energy_batt = 0;
for y = 1:pv_lifetime
    df = 1 / (1 + discount_rate)^y;
    yc = batt_om;
    if num_replacements >= 1 && ~isnan(batt_replacement_year) && y ==
       batt_replacement_year + 1
        yc = yc + batt_capex;
    end
    if num_replacements >= 2 && ~isnan(batt_replacement_year2) && y ==
       batt_replacement_year2 + 1
        yc = yc + batt_capex;
    end
    total_cost_batt   = total_cost_batt   + yc * df;
```

```
    total_energy_batt = total_energy_batt + annual_discharge * df;
end
LCOS_batt = total_cost_batt / total_energy_batt;
cost_batt_delivered = LCOE_pv / efficiency + LCOS_batt;

%% ========================
% SYSTEM LCOE (PV + Battery)
% ========================
total_cost_sys = pv_capex + batt_capex; total_energy_sys = 0;
for y = 1:pv_lifetime
    df = 1 / (1 + discount_rate)^y;
    yc = pv_om + batt_om;
    if num_replacements >= 1 && ~isnan(batt_replacement_year) && y == batt_replacement_year + 1
        yc = yc + batt_capex;
    end
    if num_replacements >= 2 && ~isnan(batt_replacement_year2) && y == batt_replacement_year2 + 1
        yc = yc + batt_capex;
    end
    total_cost_sys   = total_cost_sys   + yc * df;
    total_energy_sys = total_energy_sys + E_pv_batt_annual * (1 - degradation_rate)^(y-1) * df;
end
LCOE_system = total_cost_sys / total_energy_sys;

%% ========================
% BASELINE ANNUAL COST (no system)
% ========================
baseline_annual = E_elec_ann * grid_price + E_diesel_base * diesel_price;

%% ========================
% NPV / IRR / PAYBACK PERIOD
% ========================
capex_total = pv_capex + batt_capex;
cash_flows  = zeros(1, pv_lifetime + 1);
cash_flows(1) = -capex_total;   % year 0: initial investment

for y = 1:pv_lifetime
    deg = (1 - degradation_rate)^(y-1);
    om  = pv_om + batt_om;
    rep = 0;
```

```
    if num_replacements >= 1 && ~isnan(batt_replacement_year) && y ==
        batt_replacement_year + 1
         rep = rep + batt_capex;
    end
    if num_replacements >= 2 && ~isnan(batt_replacement_year2) && y ==
        batt_replacement_year2 + 1
         rep = rep + batt_capex;
    end
    sys_cost_y = E_pv_ann*deg*LCOE_pv +
        E_batt_ann*deg*cost_batt_delivered ...
                + E_grid_ann*grid_price + E_diesel_sys*diesel_price + om +
                   rep;
    cash_flows(y+1) = baseline_annual - sys_cost_y;
end

% NPV
t   = 0:pv_lifetime;
NPV = sum(cash_flows ./ (1 + discount_rate).^t);

% IRR (bisection)
f   = @(r) sum(cash_flows ./ (1 + r).^t);
lo  = -0.5; hi = 5.0;
for k = 1:200
    mid = (lo + hi) / 2;
    if f(mid) > 0; lo = mid; else; hi = mid; end
end
IRR = (lo + hi) / 2;

% Simple payback period (undiscounted cumulative cash flows)
cumulative = cumsum(cash_flows);
pp_idx     = find(cumulative >= 0, 1);
if isempty(pp_idx)
    PP = Inf;
else
    PP = pp_idx - 1;   % subtract 1 because index 1 = year 0
end

%% =======================
% RESULTS
% =======================
fprintf('--- LCOE / LCOS ---\n');
fprintf('PV LCOE:                     %.4f USD/kWh\n', LCOE_pv);
```

```
fprintf('Battery LCOS:              %.4f USD/kWh\n', LCOS_batt);
fprintf('System LCOE (PV+Battery):  %.4f USD/kWh\n', LCOE_system);
fprintf('\n--- Investment Metrics ---\n');
fprintf('Total CapEx:               %.0f USD\n',   capex_total);
fprintf('Baseline annual cost:      %.0f USD/yr\n', baseline_annual);
fprintf('Year 1 savings:            %.0f USD\n',   cash_flows(2));
fprintf('NPV:                       %.0f USD\n',   NPV);
fprintf('IRR:                       %.2f%%\n',     IRR * 100);
fprintf('Simple payback period:     %d years\n',   PP);
```