Food and Agriculture Organization of the United Nations

Costs and Benefits of Clean Energy Technologies in the Milk, Vegetable and Rice Value Chains

A. FLAMMINI, S. BRACCO, R. SIMS, J. COOKE, A. ELIA

INTERVENTION LEVEL

JULY 2018

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POWERING AGRICULTURE:

AN ENERGY GRAND CHALLENGE FOR DEVELOPMENT

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ACRONYMS AND ABBREVIATIONS

AC	alternating current
AD	anaerobic digestion
ADB	Asian Development Bank
AGR	acid gas removal
AHK	Auslandshandelskammer
B/C	benefit/cost (ratio)
BMC	biogas milk chiller
BOD	biochemical oxygen demand
C/N	carbon/nitrogen (ratio)
C/P	carbon/phosphorus (ratio)
CRI	Crop Research Institute
CBA	cost-benefit analysis
CH4	methane
CHP	combined heat and power
CO	carbon monoxide
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
DC	direct current
DM	dry matter
DX	direct expansion
EBRD	European Bank for Reconstruction and Development
EPA	United States Environmental Protection Agency
ERC	Energy Regulatory Commission
ESCWA	Economic and Social Commission for Western Asia
ESMAP	Energy Sector Management Assistance Program
FAO	Food and Agriculture Organization of the United Nations
FEA	financial and economic analysis
FiT	feed-in tariff
FNR	Fachagentur Nachwachsende Rohstoffe
FOB	free on board
FTE	full-time equivalent
GACC	Global Alliance for Clean Cookstoves
GBEP	Global Bioenergy Partnership
GDP	gross domestic product
GHG	greenhouse gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GRiSP	Global Rice Science Partnership
GTZ	Gesellschaft für Technische Zusammenarbeit
GVEP	Global Village Energy Partnership
H_2S	hydrogen sulfide
H_2	hydrogen
HDPE	high density polyethylene
IAEA	International Atomic Energy Agency
IBRD	International Bank for Reconstruction and Development
IBT	ice bank tanks
ICE	internal combustion engines
ICCC	Independent Consumer and Competition Commission
ICLS	International Conference of Labour Statisticians
IDB	Inter-American Development Bank
IDF	import declaration fee
IEA	International Energy Agency
IFA	International Fertilizer Industry Association
IFAD	International Fund for Agricultural Development
IFC	International Finance Corporation
IFI	international financial institution
IFPRI	International Food Policy Research Institute
ILK	Institut für Luft- und Kältetechnik
ILRI	International Livestock Research Institute
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
IPI	International Potash Institute
IPNI	International Plant Nutrition Institute
IRENA	International Renewable Energy Agency
IRR	internal rate of return
IWA	international workshop agreement
IWMI	International Water Management Institute
JFS	Japan for Sustainability
K	potassium
KES	Kenyan shilling
KPA	Kenya Port Authority
KRA	Kenya Revenue Authority
LAB	lead acid battery
LCOE	levelized cost of energy
LED	light-emitting diode
LPG	liquefied petroleum gas

MCC	milk cooling centre
N	nitrogen
N_2	nitrogen molecule
NETL	National Energy Technology Laboratory
NGO	non-governmental organization
NH_3	ammonia
NO_2	nitrogen dioxide
NO_X	nitrogen oxides
NPV	net present value
O_2	oxygen
OECD	Organisation for Economic Co-operation and Development
O&M	operation and maintenance
P	phosphorus
PAEGC	Powering Agriculture: An Energy Grand Challenge for Development
PBT	payback time
PFAN	Private Finance Advisory Network
PFP	partial factor productivity
$PM_{2.5}$	particulate matter (particles with diameter of 2.5 micrometres or less)
PM_{10}	Particulate matter (particles with diameter of 10 micrometres or less)
PNG	Papua New Guinea
PV	photovoltaic
RDL	railway development levy
REA	Rural Energy Agency
REEEP	Renewable Energy and Energy Efficiency Partnership
REFiT	renewable energy feed-in tariffs
REN21	Renewable Energy Policy Network for the 21st Century
RHG	rice husk gasification
SO_2	sulphur dioxide
SCC	social cost of carbon
SOC	soil organic carbon
SOM	soil organic matter
SDGs	Sustainable Development Goals
SEAI	Sustainable Energy Authority of Ireland
SGC	Svenskt Gastekniskt Center
SME	small- and medium-sized enterprises
SNV	Netherlands Development Cooperation
TAMPA	Tanzania Milk Processors Association
TDBP	Tanzania Domestic Biogas Programme
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
VAT	value-added tax
VC	value chain
VCA	value chain analysis
VIA	Village Infrastructure Angels
WACC	weighted average cost of capital
WB	World Bank
WHO	World Health Organization
WRI	World Resources Institute

EXECUTIVE SUMMARY

Agricultural production systems that use energy rationally and economically can be cost-effective and provide pragmatic steps toward reducing greenhouse gas (GHG) emissions and achieving several Sustainable Development Goals (SDGs). Sustainable "climate-smart" and "energy-smart" agrifood processing and delivery systems can result in significant structural changes, improved livelihoods and enhanced food security for rural communities in many countries.

The Food and Agriculture Organization of the United Nations (FAO) published the report "Opportunities for Agrifood Chains to become Energy-Smart" in November 2015 under the international initiative "Powering Agriculture: An Energy Grand Challenge for Development" (PAEGC). Selected food supply chains for milk, rice and vegetables (tomatoes, carrots and beans) were assessed for their energy inputs at each step along the specific value chain. Analyses of these agrifood value chains, at both large and small scales, identified priority stages, entry points and interventions where clean energy solutions could be introduced. They also highlighted opportunities to reduce energy demand through improved efficiency.

The subsequent study, presented in this report, focused on the same three food supply value chains as the original report and concentrated on similar key clean energy technologies. Their costs, benefits and sustainability potentials were analysed together with unintended impacts at the intervention level (e.g. at farmer or food processor level). A methodological approach was developed (Section 3) to provide a sound and comprehensive cost-benefit analysis (CBA). The potential added value of these technologies for different stakeholders was then considered using selected case studies (Section 4).

The methodological approach highlights hidden environmental and socio-economic costs of interventions, such as government-subsidized fossil fuel, which are often borne by non-economic operators. Such costs and co-benefits were therefore included and highlighted in the analysis and compared to a simple financial analysis to inform investments. The CBA approach includes four main steps (Figure ES.1).

FIGURE ES.1. Cost-benefit analysis: Summary of main steps.

Source: Authors.

1. Identify and describe both the benchmark scenario (which normally consists of fossil fuel-powered and/or inefficient technologies) and the post-energy intervention scenario (where the technology is adopted). For instance, an irrigation system can be powered by a diesel pump (benchmark scenario) or by a solar photovoltaic (PV) powered pump (post-energy intervention scenario).

2. Identify the investment costs, including capital and operating costs, and benefits. For the economic analysis, market prices are converted into economic/shadow prices to better reflect the social opportunity benefits and costs of the investment. This can be done by removing transfer payments such as taxes and subsidies, quantifying positive and negative externalities not borne by the investor(s) and, when possible, monetizing them.

3. Determine the financial and economic incremental net flows for the investment that result from comparing costs and benefits of the project with the benchmark scenario. Project performance indicators such as financial and economic net present value (NPV), internal rate of return (IRR), benefit/cost (B/C) ratio or payback time are then calculated by applying discounting to these flows.

4. Perform a sensitivity analysis to assess the main risks and uncertainties.

A range of 12 impact indicators was developed to assess potential non-monetized environmental and socio-economic impacts that could arise when introducing an innovative clean energy technology (Table ES.1). Each description illustrates the indicator's relevance to clean energy interventions (typically the introduction of an energy efficient or a renewable energy technology in the food chain) and its relevance to sustainability.

TABLE ES.1. Indicators for non-monetized environmental and socio-economic impacts.

Indicator name	Indicator description
Socio-economic impacts	
Access to energy	Change in access to energy
Household income	Change in monetary in-flows, such as wage and revenues, and out-flows
Time saving	Change in time spent performing unpaid agricultural and/or household activities
Employment	Net jobs created along the agrifood value chain, and shares of: • skilled or unskilled jobs, disaggregated by gender if possible • temporary part-time or indefinite full-time jobs, disaggregated by gender if possible
Environmental impacts	
Soil quality	Change in soil quality, in particular in terms of soil organic carbon
Fertilizer use and efficiency	Change in (i) the amount of chemical fertilizer applied and (ii) partial factor productivity
Indoor air pollution	Emissions of $PM_{2.5}$, PM_{10}, NO_X, SO_2 and other pollutants
Water use and efficiency	Change in amount of water used (i) in absolute terms and (ii) per quantity of output
Water quality	Change in pollutant loadings, measured as (i) annual nitrogen (N) and phosphorus (P) content, (ii) temperature change, and (iii) pH change of the watershed
Food loss	Amount of food loss avoided as a direct consequence of the energy intervention
Land requirement	Productive land converted as a direct consequence of the energy intervention
GHG emissions	Change in (i) the absolute amount of GHGs emitted and (ii) emissions per unit of product as a result of the intervention

Source: Authors.

Costs were compiled for each of the selected agrifood clean energy technologies, based on case studies where data were available (Section 4). A CBA for intervention level was then conducted to assess the impacts from adopting a specific technology, such as an improvement in the efficient use of energy[1].

Data from six case studies were used in a *financial analysis* to demonstrate whether an investment in a particular technology would be financially viable for economic operators such as farmers and food processors. In addition, an *economic analysis* highlighted the externality costs and benefits of the development and uptake of a specific technology as borne by non-economic operators such as government or society.

Although this study focuses on energy interventions in the milk, vegetable and rice value chains, the methodology is applicable to any energy intervention in all food value chains.

The energy interventions analysed were not selected on the basis of their relevance to reduce fossil fuel dependency along the value chains but rather by the availability of data and real case studies stemming from the work of FAO and partners. A description and discussion about the possible interventions in the milk, vegetable and rice value chains and their relevance in terms of energy, water and GHG impacts can be found in FAO and USAID (2015). Pro-poor technologies were given particular emphasis in the selection and assessment of technologies in each of the three value chains.

1 Green indicates an additional positive non-monetized impact, red a negative one and orange an impact that could be positive or negative (very context-specific and more information from the case studies would be required).

KEY FINDINGS

Although an economic CBA does not provide information on the economic efficiency, political feasibility, legality, or social and cultural acceptability of a project, it can **inform decision-makers about the distribution of costs and benefits of a clean-energy project investment** across stakeholders.

A CBA cannot provide precise quantitative estimates of all future costs and benefits since certain flows are very difficult, if not impossible, to monetize. One example is the impact of clean energy technologies on gender issues, since specific activities are typically carried out either by men (such as running a diesel engine) or by women (such as tending a domestic biogas plant, or selling agricultural products at the local market). A gender perspective was integrated by looking at the impact of adopting a certain technology on women through such factors as control of income from new agrifood technologies; amount of time and labour saved; benefits from increased productivity; youth employment opportunities; access to and control of land and water for agriculture; access to capital; and the ability to spend it. Gender analysis in the case studies was limited owing to a lack of gender-sensitive information, including sex-disaggregated data. However, one conclusion from the analysis is that there were **no evident general trends as to how gender issues would benefit from clean-energy interventions;** each case has its own specific benefits.

The study highlights that the success of the initial financial investment, needed to introduce the clean energy intervention across the three agrifood chains, can be assessed by the financial returns to the investor and/or operator. However, any co-benefit or cost that does not contribute to financial returns can have an important impact on society. Additional revenue streams arising from increased productivity, losses avoided as a result of adopting a technology, or the production of biogas from food process residues and other organic wastes should also be included in the analysis. Indeed, in some case studies, investments leading to negative financial returns are positive overall if co-benefits are incorporated. The difference between financial and economic performance is highlighted in Table ES.2 along with those non-monetized and/or non-quantified impacts.

TABLE ES.2. Financial and economic analysis results for the six case studies selected from the milk (M), vegetable (V) and rice (R) value chains.

Case study	Initial capital investment	Financial assessment (how attractive the investment is from the investor point of view)		Economic assessment (how attractive the investment is from a development/society point of view)				Investment appraisal results
		Financial IRR (%)	Financial NPV (thousand US$)	Economic IRR (%)	Economic NPV (thousand US$)	Monetized impacts (already included in the economic IRR and NPV)	Non-monetized impacts (not included in the economic IRR and NPV)	
M1. Biogas for power generation	570	4	–220.8	7	–140.6	Fertilizer use and efficiency; GHG emissions; employment	Water quality	Not attractive financially. Slightly more interesting from the economic point of view, although not attractive. Additional potential impact on water quality.
M2. Biogas-powered domestic milk chiller	1.6	85	6.3	92	7.5	Fertilizer use; indoor air pollution; food loss reduction; household income; GHG emissions; employment	Soil quality; water use and efficiency; water quality; access to energy; time savings	Very attractive, especially from the economic point of view. Additional variable impact on water and time savings.
M3. Solar milk cooler	40	12	1.5	17	11.9	Food loss reduction; GHG emissions; household income	Water use and efficiency; water quality	Moderate attractiveness although it improves from an economic point of view. Additional variable impact on water.
V1. Solar-powered water pumping	0.65	27	0.3	51	1.0	GHG emissions; access to energy; household income; employment	Time savings	Very attractive, especially from the economic point of view.
R1. Rice husk gasification	76	–8	–43,8	17	7.9	GHG emissions; employment	Soil quality; water use and efficiency	Not attractive financially but economically. Additional negative impacts on soil quality and water use.
R2. Solar-powered domestic rice processing	4.9	13	0.9	43	11	GHG emissions; access to energy; household income; employment	Water use and efficiency; water quality; time savings	Moderate attractiveness from a financial point of view which improves significantly from an economic perspective. Additional potential impact on water quality and time savings.

Source: Authors.

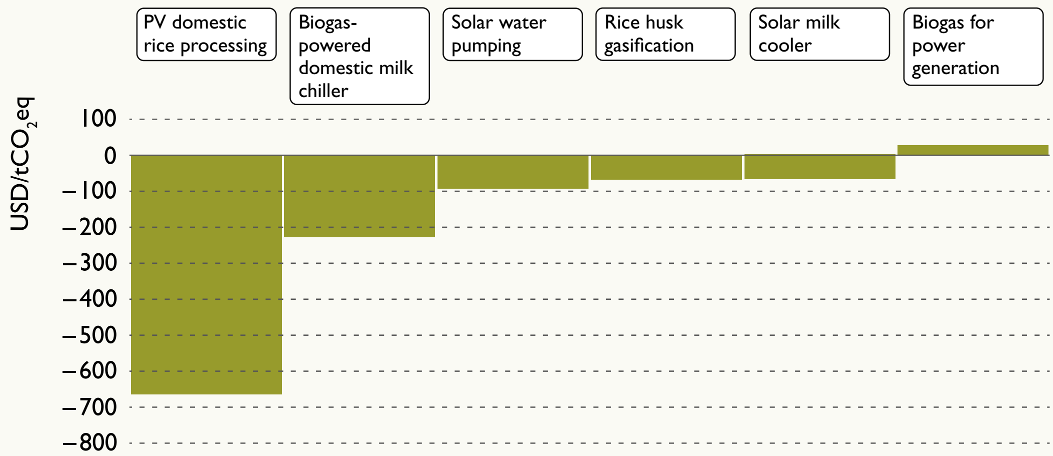
Even in a case where an investment is financially unattractive for the individual operator (such as the rice husk gasification case study in Cambodia), the overall economic returns on investment can become positive when net co-benefits are included. In such cases, **from the society perspective, it could make sense to support or subsidize the investment in order to make it financially attractive** (e.g. introducing a subsidy to support the uptake of the technology).

An important effect from clean-energy interventions is the reduction of fossil fuel consumed, and hence the amount of GHGs emitted. The **co-benefit of the avoided social cost due to GHG emission reduction can be significant but is heavily dependent on the monetary value given to it.** In this report, a conservative social cost of US$36/t$CO_2$ was assumed. However, it is appreciated that social cost estimates vary widely in the literature.

When undertaking a CBA, it could be useful to assess the performance of energy interventions to mitigate GHG emissions in the case studies as additional information when making investment choices. The GHG mitigation cost of selected interventions assessed in this report can be expressed as economic NPV (hence including monetized co-benefits and costs) divided by the total amount of CO_2eq reduced by the intervention during its lifetime. Since most of the case studies showed a positive economic NPV, the associated mitigation cost is negative, with the only exception of biogas for power (Figure ES.2). In other words, there is generally an overall economic benefit associated with GHG mitigation over the timeframe of the investments analysed.

FIGURE ES.2. Mitigation costs (economic NPV/tCO_2eq avoided) for the six case studies.

Source: Authors.

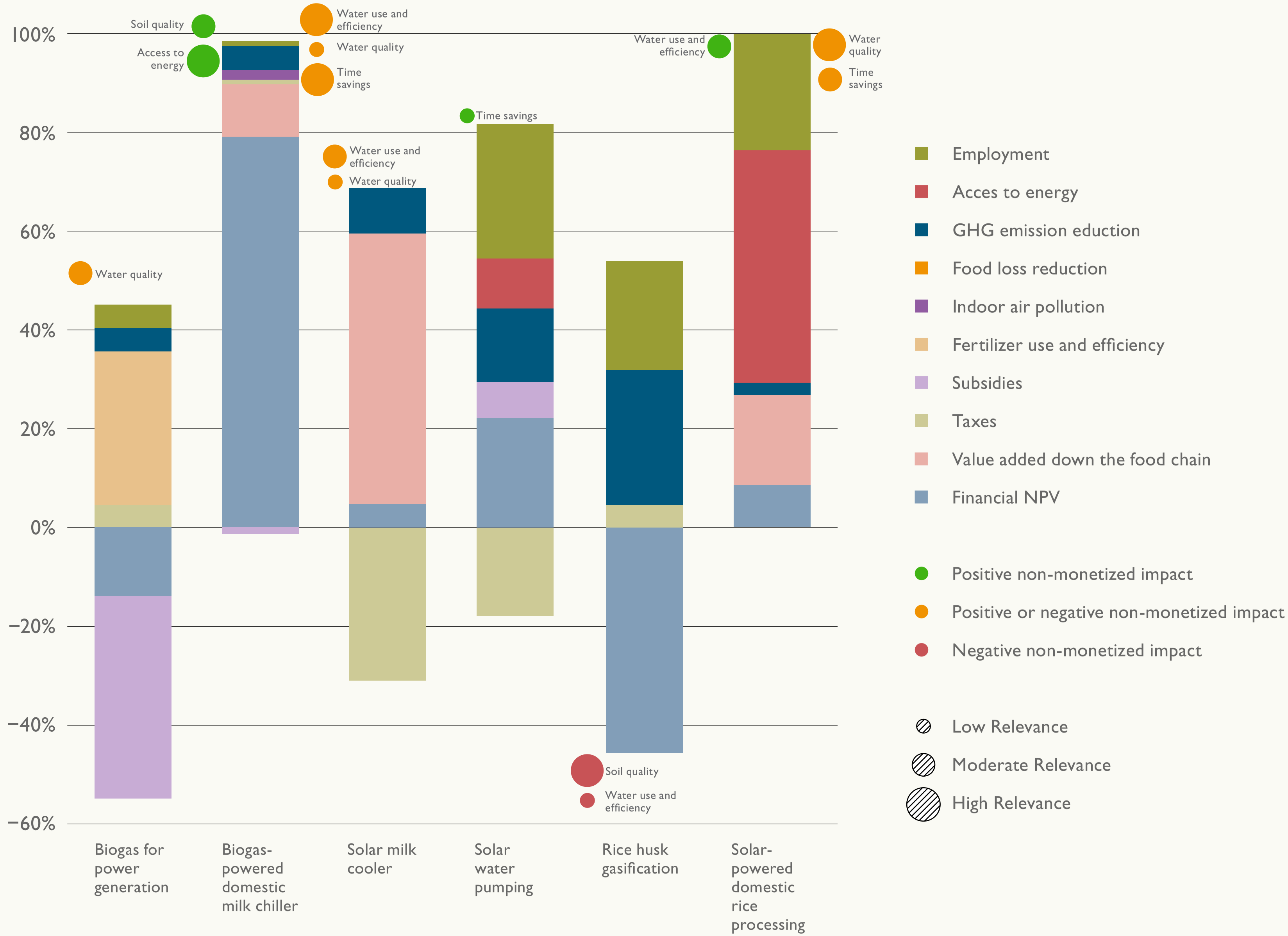


An analysis of the distribution of co-benefits also provides useful insights on the return of each dollar invested in a specific energy intervention (Figure ES.3). **Interventions that maximize the non-financial returns are expected to spread the benefits amongst society.**

FIGURE ES.3. Shares of financial and non-financial co-benefits (positive) and costs (negative) for the six case studies.

Note: Taxes and subsidies can be positive or negative benefits. For example, if the intervention is subsidized, that subsidy is a cost for society, whereas if the intervention reduces the amount of taxes paid to society, this is a negative benefit (or a cost) for society.

Source: Authors.



Green indicates an additional positive non-monetized impact, red a negative one and orange an impact that could be positive or negative (very context-specific and more information from the case studies would be required).

From the six energy intervention case studies analysed (which are just a small sample of all possible energy interventions), some preliminary findings can be drawn. For example, the **smaller-scale applications are more likely to achieve more diversified co-benefits,** especially on socio-economic aspects. Systems such as small-scale milk chillers, small-scale solar water pumps and solar-powered rice processing systems typically target farmers and their families as well as local food processors – often in remote rural areas where access to modern energy services is often constrained. In this context, a clean-energy intervention can have the added benefit of reducing drudgery, particularly for women, and improving lifestyles. In some cases, access to electricity enables communities to start new businesses (including small businesses such as copy shops, internet cafés or mobile phone charging services). These co-benefits are relevant in economic terms and can significantly exceed the financial benefits.

The economic performance obviously depends on the specific context under which an energy intervention is introduced, since **local taxes, markets, energy prices and subsidies have significant influence.** For example, where deployment of renewable energy is publicly subsidized (as was the case for biogas-for-electricity generation plants in the case study), the investment may not be economic since the subsidies are a cost on society.[2] The actual cost of energy from a conventional source in the location of an intervention (such as grid electricity tariffs or diesel fuel prices), and the extent of any government subsidy, are key variables to determine the economic attractiveness of a clean-energy option.

The co-benefit of reducing food losses or improving food quality due to the introduction of a clean energy technology (as is the case for off-grid milk cooling facilities and solar-powered cold storage systems) **can be very relevant.** It can increase the amount, and by consequence the total value, of food products that enter into the market. This can have an impact on subsequent steps along the value chain. For example, introducing a milk chiller on a small farm will reduce milk spoilage and can have positive impacts where local milk supply is limited, and the local market is not well developed or functioning inefficiently (as is typical in rural and remote areas of developing countries). The adopter of the clean energy technology will directly benefit from increased revenue, but additional value may also occur along the supply chain such as for milk processors, transport businesses and retailers. Food loss reduction thus has **a multiplier effect, which tends to be more significant in longer value chains** (such as the milk chain, as compared to the rice or vegetable chains).

Furthermore, the impacts of the six energy interventions analysed in this report have a direct positive or negative link to the achievement of several of the 17 SDGs, in particular:

- zero hunger (SDG 2)
- good health and well-being (SDG 3)
- gender equality (SDG 5)

2 This is particularly true for fossil fuel subsidies, since the cost of the subsidy adds to the societal cost in terms of environmental pollution.

- clean water and sanitation (SDG 6)
- affordable and clean energy (SDG 7)
- decent work and economic growth (SDG 8)
- responsible consumption and production (SDG 12)
- climate action (SDG 13)
- life on land (SDG 15)

Linkages can be found between the different energy interventions and specific SDGs (Table ES.3), based on the relevance of impact indicators to specific SDG targets (Section 4.4), and the relevant environmental and socio-economic impacts of each intervention (Section 3.3).

TABLE ES.3. **Link between selected agrifood energy technologies and the SDGs (above) and targets (below).**

SDGs / Technology	2 ZERO HUNGER	3 GOOD HEALTH AND WELL-BEING	5 GENDER EQUALITY	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	15 LIFE ON LAND
Biogas for power generation	Targets 2.1, 2.2, 2.3 and 2.4	Target 3.9	Target 5.8	Targets 6.3 and 6.4	Target 7.1	Targets 8.2 and 8.5	Targets 12.2, 12.3 and 12.4	Target 13.2	Targets 15.3 and 15.5
Biogas-powered domestic milk chiller	Targets 2.1, 2.2, 2.3 and 2.4	Target 3.9	Target 5.8	Targets 6.3 and 6.4	Target 7.1	Targets 8.2 and 8.5	Targets 12.2, 12.3 and 12.4	Target 13.2	Target 15.3
Solar milk cooler	Targets 2.1, 2.2 and 2.3	–	Target 5.8	Targets 6.3 and 6.4	Target 7.1	Targets 8.2 and 8.5	Target 12.3	Target 13.2	–
Solar cold storage for vegetables	Targets 2.1, 2.2 and 2.3	–	Target 5.8	Target 6.4	Target 7.1	Targets 8.2 and 8.5	Targets 12.2 and 12.3	Target 13.2	–
Solar water pumping	Target 2.3	–	Target 5.8	Target 6.4	Target 7.1	Targets 8.2 and 8.5	Target 12.2	Target 13.2	–
Rice husk gasification	Targets 2.3 and 2.4	–	Target 5.8	Target 6.3	Target 7.1	Targets 8.2 and 8.5	Target 12.4	Target 13.2	Targets 15.3 and 15.5
Solar-powered rice processing	Targets 2.1, 2.2 and 2.3	Target 3.9	Target 5.8	Target 6.4	Target 7.1	Targets 8.2 and 8.5	Targets 12.2 and 12.3	Target 13.2	–

Target 2.1	By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round
Target 2.2	By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons
Target 2.3	By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment
Target 2.4	By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality
Target 3.9	By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination
Target 5.8	Enhance the use of enabling technology, in particular information and communications technology, and to promote the empowerment of women
Target 6.3	By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally
Target 6.4	By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity
Target 7.1	By 2030, ensure universal access to affordable, reliable and modern energy services
Target 8.2	Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors
Target 8.5	By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value
Target 12.2	By 2030, achieve the sustainable management and efficient use of natural resources
Target 12.3	By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses
Target 12.4	By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment
Target 13.2	Integrate climate change measures into national policies, strategies and planning
Target 15.3	By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world
Target 15.5	Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species

Source: Authors' compilation of SDG targets.

Energy investments in agrifood chains are more closely linked with the achievement of SDGs 2, 6, 7, 8, 12, 13 and 5.[3] The interventions involving biogas (and digestate) production have crosscutting impacts on all nine of the above-mentioned SDGs, while solar-based interventions impact on a smaller number. However, further analysis of more case studies is required to confirm these linkages.

KNOWLEDGE GAPS

The findings above are based on the six case studies analysed in this report. Whilst informative, this analysis cannot be accepted with a high degree of confidence since the sample of case studies was limited. **More case studies are needed to validate the key findings** and reliably identify trends. Organizations that are able to access data and information on the impacts of energy interventions in agrifood chains from their project portfolio could help fill this knowledge gap. Such organizations include PAEGC partners, the Renewable Energy and Energy Efficiency Partnership (REEEP), the International Renewable Energy Agency (IRENA), FAO as well as development banks, government agencies, and non-governmental organizations (NGOs) running or managing programmes that target the agrifood sector.

The methodology of CBA also suffers from knowledge gaps. Public economics studies government policy through the lens of economic efficiency, equity and the ability to quantify/monetize project impacts; yet **no method can truly monetize positive and negative environmental and social impacts.** For this reason, the methodology used is non-prescriptive on how impacts should be monetized, but provides guidance on how non-monetized environmental and socio-economic impacts could be measured in a quantitative manner. This is achieved through the 12 impact indicators mentioned above (Section 3.3), which can be used to measure impacts of energy interventions in agrifood chains.

This set of indicators was specifically designed to be applied to any energy intervention (typically an energy efficiency or renewable energy intervention) in the food chain. However, the indicators selected and the associated methodology may prove to be irrelevant or unsuitable to cover the complete range of possible energy interventions. **A systematic pilot testing of the indicator set, encompassing a diversified number of energy interventions, would inform the future revision and adjustment of the indicators.**

Countries that test the indicators and the economic CBA will obtain valuable information regarding the performance of energy interventions. **The testing of the indicators can provide an understanding of how to establish a systematic monitoring or screening of energy investments in the agrifood chain based on a consistent methodology.** This would result in an enhanced understanding of how the contributions of food and energy investments to national sustainable development are evaluated. It is also appreciated that, given the data requirements and the broad range of scientific

3 A focus on linkages between renewable energy in general and the SDGs can be found in the most recent edition of IRENA's REthinking Energy report (2017) available at http://www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=36&CatID=141&SubcatID=3802. Among other issues, it notes the important role decentralized renewable solutions can play in the agrifood chain.

expertise needed, technical and financial assistance may be required by some countries in order to undertake such a CBA and use it to inform policy-making.

RECOMMENDATIONS

The following are general recommendations for how to best support rural economic development by promoting clean energy solutions in agrifood value chains:

(i) From a sustainable development perspective, investment choices should always consider non-financial costs and benefits. For the energy interventions analysed, net economic benefits largely exceed net financial benefits. In some cases, the net economic benefits are positive even if the investment is financially unattractive.

(ii) Since the monetization of all co-benefits can be complex, it is recommended to adopt a consistent set of indicators to measure non-monetized impacts of energy interventions in agrifood chains. The set of indicators used here serves this purpose but could be further piloted and revised.

(iii) The interventions that maximize non-financial returns should be prioritized from the perspective of sustainable development – since they are expected to spread the benefits amongst society.

(iv) Smaller-scale technologies should be prioritized to maximize the diversification of co-benefits. Such systems typically target farmers and their families as well as local food processors. In this context, a clean-energy intervention can have the added benefit of reducing drudgery and improving lifestyles (for example, access to electricity to start new businesses).

(v) Energy interventions that reduce food losses or increase food quality should be prioritized since the co-benefits down the food chain can be major – especially in food insecure regions. Energy interventions that reduce food wastage near the beginning of a long value chain have important multiplier effects, since more food is available. Longer food value chains (i.e. with a wider range of actors such as the milk chain compared to the rice chain) can potentially benefit the most from interventions reducing food losses. For example, the local production of better quality milk to meet the growing demand for milk products in poor isolated regions has strong economic development potential, especially when local demand of good quality milk exceeds the availability (such as in the case of biogas milk cooling in rural Tanzania).

(vi) Access to inputs, services and decision-making between men and women – at home, on the farm, in cooperatives and throughout the value chain – mean that energy interventions have an impact, positive and/or negative, on gender equality. However, no general trend by energy intervention or value chain could be drawn from the analysis and it is recommended to assess impacts on gender issues on a case-by-case basis. The systematic promotion of gender equality in energy interventions should be improved, from design and problem identification to complementary services, monitoring and evaluation and the recruitment of staff.

(vii) An economic CBA should be undertaken as a guide to choose between investments, assuming that data and information exist that provide an accurate estimate of net benefits. In addition, economic efficiency, political feasibility, legality, social and cultural acceptability of a project are likewise important aspects to be considered as they can determine the success of an energy intervention.

(viii) In an economic CBA, it is important to carefully consider taxes, subsidies, and added value along the agrifood chain since they can significantly modify the results.

(ix) Since the assumed social cost of GHG emissions can be a major variable to determine economic co-benefits, it is important to use consistent assumptions when assessing and comparing different energy interventions.

(x) In off-grid areas or regions with an unreliable energy grid, it is important to prioritize energy interventions that contribute to energy access as a co-benefit (e.g. those that make surplus modern energy available for use by families and communities, including to those outside the specific food value chain). Access to clean, reliable and affordable energy, especially in rural areas of developing countries, will help reduce poverty, enable new businesses and can significantly decrease energy supply costs – including for simple energy services such as lighting or mobile phone charging. Synergies between energy needs for food and other village-level necessities should be considered when designing solutions that can meet diverse energy needs and maximize sustainable development impacts (e.g. a micro-grid with irrigation pumps and agro-processing equipment as anchor loads).

(xi) Investments in energy interventions in the agrifood chain have a direct impact on achieving the SDG targets since they can affect positively or negatively at least 9 of the 17 total SDGs. Synergies and trade-offs among SDGs and targets need to be carefully considered in a truly crosscutting and interdisciplinary perspective by giving special attention to the water-energy-food nexus.

I. INTRODUCTION

"Powering Agriculture: An Energy Grand Challenge for Development" (PAEGC) is an international initiative launched in 2012 that brings together the Federal Ministry for Economic Cooperation and Development (BMZ), represented by the *Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH*; the United States Agency for International Development (USAID); the Swedish International Development Agency (SIDA); the United States Overseas Private Investment Corporation (OPIC); and Duke Energy. It supports new and sustainable approaches that accelerate the development and deployment of clean energy solutions to increase agriculture productivity and/or value for farmers and agribusinesses in developing countries and emerging regions that lack access to reliable, affordable clean energy.

To contribute to the overall objective of the PAEGC initiative, the Food and Agriculture Organization of the United Nations (FAO) and GIZ worked together to strengthen the understanding and knowledge about sustainable energy solutions in agriculture. A first milestone was the preparation of a comprehensive study report "Opportunities for Agrifood Chains to become Energy-Smart"[4] launched in 2015. It provided an updated overview of the energy technologies that can be introduced along the relevant "hot points" in the production chain of selected food products and the importance of the nexus between agriculture, energy and water. The study focused on three specific value chains: milk, rice and vegetables (the latter restricted to tomatoes including greenhouse production, beans, and carrots, with various markets for each, including fresh, canned, paste and frozen products).

The follow-up study, as presented in this report, used the same three agrifood value chains, each linked with clean energy technologies. However, further analysis was made using specific costs and benefits at the intervention level and a methodology was devised to highlight the co-benefits associated with each technology.

Decoupling the dependence of an agrifood value chain from fossil fuels could lead to several benefits, including increased resilience from shocks in the energy market, mitigation of greenhouse gas (GHG) emissions and, often, economic benefits for the operators. However, any reduction of fossil fuel dependence should not happen at the expense of food productivity or quality, considering that the global food system will be required to produce significantly more in the next few years as demand increases, especially for protein.

The overall aim of this report is to identify and highlight the costs and benefits associated with investment in clean energy technologies and systems in the food sector that can accrue to stakeholders in the agrifood industry including farm

4 Available on Energypedia at https://energypedia.info/wiki/Opportunities_for_Agri-Food_Chains_to_become_Energy-Smart as well as on the FAO Document Repository.

businesses, farmers' associations, retailers, training institutions, food processing companies, policy-makers, investors and financiers. To achieve this, an assessment was made of:

- the specific financial and economic implications of the identified energy technologies in the agrifood sector, including environmental and social impacts;
- the suitability of the identified technologies for a specific development context;
- the expected return on investment; and
- the enabling conditions and policies needed to trigger pro-poor investments in the food sector with regard to clean energy solutions.

Selection of the clean energy technologies and systems in each of the three value chains was mainly based on their potential to add value and/or reduce fossil fuel energy demand at key points along the value chain. Their costs and level of sustainability were analysed, while possible unintended impacts (at the intervention level) were also included. The study considered how the introduction of clean energy technologies or systems would change the cost structure for the operators, including hidden costs often borne by non-economic operators as a result of schemes such as government-subsidized fossil fuel. An analytical methodology was developed to permit a sound and comprehensive cost-benefit analysis (CBA).

Special attention was given to pro-poor technologies and gender distribution along the selected value chains as female/male dominated segments may be correlated with investment power, target markets, and readiness to assume risks. The report includes a discussion on the potential of the various technologies to contribute to gender equality.

The report is divided into four sections. Section 2 illustrates the main concepts needed for analyses of agriculture and food value chain interventions. Section 3 presents the steps to plan investment in clean energy interventions (or technologies) in value chains, and discusses how to include externalities in the assessment, such as environmental, economic and social impacts. It highlights the difference between financial and economic costs and benefits related to the investment. Section 4 focuses on specific energy interventions (or technologies) and real case studies selected as examples for the three value chains under analysis. The technologies, their costs and expected impacts are discussed. The methodology illustrated in Section 3 is then applied to the case studies. Finally, Section 5 provides key findings, knowledge gaps and recommendations stemming from the analysis.

2. AGRIFOOD VALUE CHAINS AND ENERGY INTERVENTIONS

Traditionally, agricultural production has depended on manual labour, animal power and biomass combustion to provide energy for storage, processing, transport and distribution of food products. Throughout the agrifood value chain, these forms of energy inputs have largely been displaced by fossil fuels as agriculture has become more industrialized, and both farm production and food processing have become more intensive. The associated industries have become largely dependent on fossil fuel inputs for activities such as heating, cooling, transportation, conveying, water pumping, lighting, animal comfort, mechanical power, etc. (FAO and USAID, 2015). Hence, provision of modern energy services is essential throughout the agrifood chain.[5]

Sustainable energy interventions in an agrifood enterprise include the introduction of renewable energy technologies and energy efficiency measures. Energy efficiency gains in food production can be seen as an improvement in energy intensity: obtaining the same output or service by using less energy. Fossil fuels are not only used in the food production but also for its processing, distribution and consumption. Food processing is largely dependent on electricity and heat. This provides opportunities for efficiency investments and new business models, as energy provision is a cost not only to the processors but to society as a whole, since the use of fossil fuels impacts negatively on the environment (Deloitte, 2013). A more energy-efficient food chain would obtain the same result by using less energy and by reducing energy losses.

Renewable energy technologies are not only relevant for rural communities without access to modern energy services but also to food processing plants – especially where conventional energy is particularly expensive (for example due to poor road infrastructure) and where the national electricity grid is unavailable or unreliable. In such locations, small-scale hydro, wind, geothermal, bioenergy and solar power systems can replace fossil fuel generators to produce renewable electricity and heat for use in the production, storage, handling and processing of food products.

Since investment in the food-energy nexus can affect different stages of the food value chain, the overall impacts should be assessed by adopting a value-chain approach.

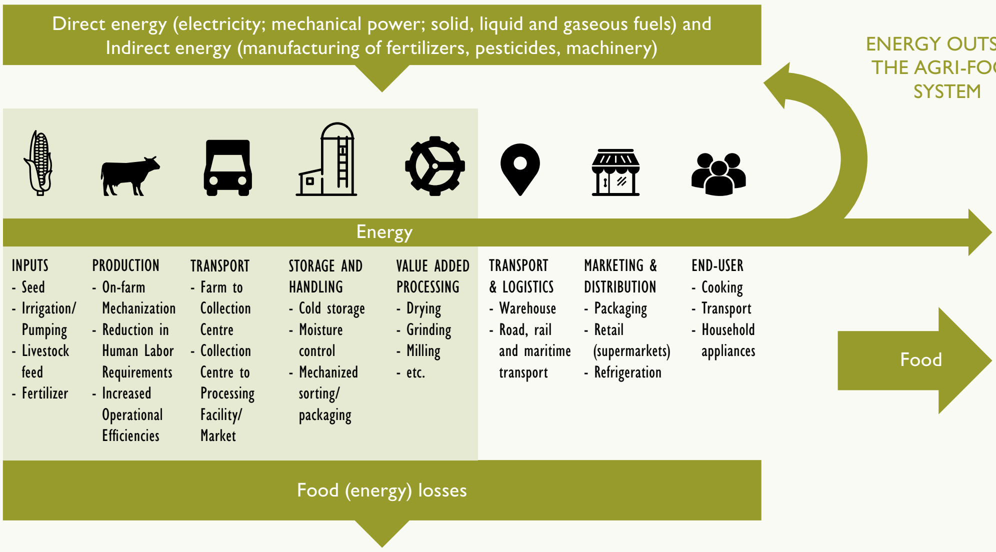
5 The socio-economic benefits of introducing decentralized renewable energy technologies in the agrifood chain have been also analysed in IRENA's publication (2016a).

2.1. VALUE-CHAIN APPROACH

Each segment of the value chain carries its own challenges for efficient and cost-effective energy provision whilst minimizing the dependence on fossil fuel. Investments in renewable energy and energy efficiency are assessed for agricultural production and food processing activities, but not for the transport and logistics, marketing and distribution stages, or for end-user food preparation and consumption (and neither for inputs) (Figure 2.1).

FIGURE 2.1. Points along the agrifood chain where clean energy technologies can be implemented.

Source: FAO and USAID, 2015.



The term "value chain" as used here refers to a set of inter-dependent economic activities, starting with the production of a primary commodity and ending with its processing into a consumer product. The aim of this study was not to perform detailed value chain analyses (VCAs)[6], but rather to adopt a value-chain approach while analysing the impacts, costs and benefits of energy interventions from the economic, social and environmental points of view. The study focuses on the milk, vegetable and rice value chains in emerging and developing economies and analyses selected energy interventions for each value chain. It will be complemented by a further study focusing on the economic impacts at national level.

6 See FAO (2013) for Methodological Guidelines for a Quantitative Approach in a VCA.

2.2. AGENTS AND STAKEHOLDERS

A first step to evaluating the sustainability performance of investments is to identify the objectives and capacities of the investors. Therefore, relevant stakeholders have to be listed and their economic, social and environmental objectives defined. All stakeholders need to be informed regarding the expected outcomes of the energy intervention. Their contribution to the decision-making process is also highly encouraged as they become aware of the local context and its challenges.

In VCA, an economic agent is defined as the subject carrying out a set of integrated operations of economic relevance, aimed at producing a given output. The agent can be a person, such as a farmer or food processor, or a legal entity, for example an agrifood company or a farmers' cooperative. The term "agent" is intended here as the representative of a group of individuals sharing common characteristics, or the group itself (FAO, 2013).

Agents that commonly intervene at different steps of agrifood value chains and that are likely to be impacted by the economic, social, and environmental changes induced by the introduction of a new energy technology include:

- farmers' associations and small-scale farmers
- women's cooperatives
- transport businesses and retailers
- agrifood companies
- energy companies
- start-up companies operating in energy/food sectors
- non-governmental organizations (NGOs)
- consumers
- practitioners and training institutions
- policy-makers

Stakeholders that are affected by the technology switch need to be included in the value chain analysis. For example, small-scale farmers that have experienced the material change induced by the technology are more likely to deliver valuable information for the CBA than practitioners that have only witnessed the change. Data are not always readily available, especially for pro-poor technologies, hence consultation of local stakeholders adds substantial information.

Value chain (VC) actors are supported by business development providers who do not take ownership of the product, but play an essential role in facilitating the value-creation process. Along with the VC actors, these support providers represent the extended VC. Three main types of support provider can be distinguished (FAO, 2014c):

(i) providers of physical inputs, such as seeds at the production level or packaging materials at the processing level;

(ii) providers of non-financial services, such as field spraying, storage, transport, laboratory testing, management training and market research; and

(iii) providers of financial services. These are separated from non-financial services because of the fundamental role played by working capital and investment capital in getting the VC on a path of sustained growth.

The three types of support can in practice be delivered as a package by a single provider (e.g. seed and fertilizer, insurance and on-credit, with built-in extension services). Support providers can be private sector, public sector or civil society organizations and can be directly part of the value chain governance structure (e.g. services embedded in out-grower contracts) (FAO, 2014c).

2.3. ADDING VALUE ALONG AGRIFOOD CHAINS

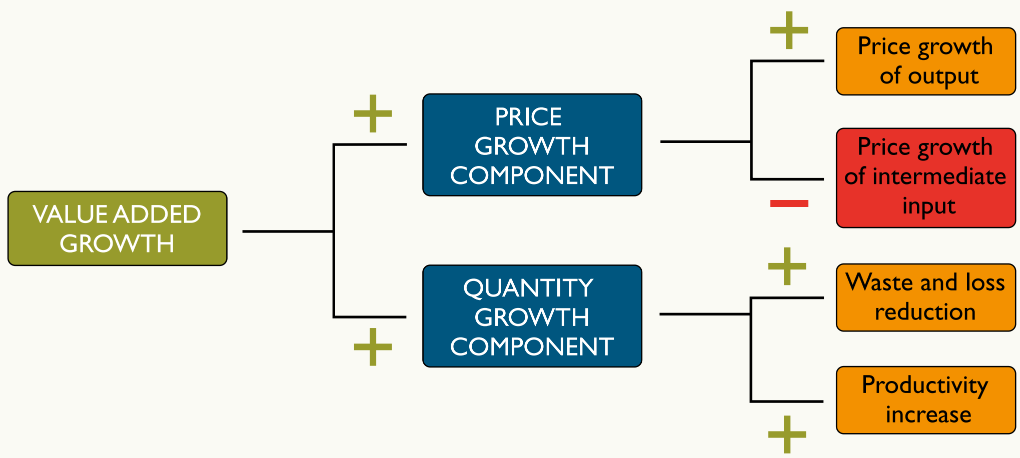
For a CBA, a value can be attributed to the inputs added by each stakeholder in the context of an energy intervention. Value can be added to an intermediate agrifood product not only by processing, sorting and packaging, but also by storing (value increasing over time) and transporting (value increasing over space) (FAO, 2014c).

"Value added" can be more formally defined as the amount by which the value of a good is increased at each stage of its value chain, exclusive of the costs of producing it. The value of a product depends on its price, its cost of production (linked to the price of intermediary inputs) and its quantity (Figure 2.2). Therefore, an increase of the value added along a value chain can either relate to an increasing output (through larger volumes or higher prices) or to decreased costs of intermediary inputs.

FIGURE 2.2. A breakdown of the concept of value-added growth in a value chain.

Note: + and – indicate respectively a positive and a negative effect on value-added growth.

Source: Authors.



In terms of quantity, for example, a reduction in waste and/or loss, or an improvement in productivity can increase the value added along the value chain. For the price component, the value that is created in an agrifood VC depends on the price of intermediate inputs, such as salaries and wages for employees; net profits for asset owners; taxes and subsidies; and the final price paid by the consumers for the output (FAO, 2014c).

2.4. SUSTAINABILITY OF VALUE CHAINS

The sustainability of the VC plays out simultaneously along the economic, social and environmental dimensions (FAO, 2014c):

- Economic dimension: An existing or proposed upgraded VC is considered sustainable if the required activities at the level of each actor or support provider are commercially viable (profitable for commercial services) or fiscally viable (for public services). This happens, for example, when a food processor uses an energy source more efficiently to perform the same economic activity.

- Environmental dimension: Sustainability is determined largely by the ability of VC actors to show little or no negative impact on the natural environment from their value-adding activities. For example, a farmer can improve his or her sustainability by making use of an energy source with lower GHG emissions to perform the same activity. Where possible, the activities should show a positive impact.

- Social dimension: Sustainability refers to outcomes that are socially and culturally acceptable in terms of the distribution of the benefits and costs associated with the increased value creation. For example, introducing clean energy technologies may lead to land use change or land requirement which may generate conflicts if the local conditions are not carefully analysed and local stakeholders are not properly engaged.

The VCA can be guided by the sustainable food framework (FAO, 2014c). Measurement of VC performance before and after it is improved or upgraded is based on the multi-dimensional concepts of value added and sustainability (Figure 2.3):

- The first phase is to "measure performance" by assessing a VC in terms of the economic, social and environmental outcomes that it actually delivers relative to an initial vision of what it could deliver in the future.

- The second phase is to "understand performance" by identifying the core drivers of performance (or the root causes of under-performance) by taking into account (i) how VC stakeholders and their activities are linked to each other and to their economic, social and natural environment; (ii) what drives the behaviour of individual stakeholders in their business interactions; and (iii) how value is determined in end markets.

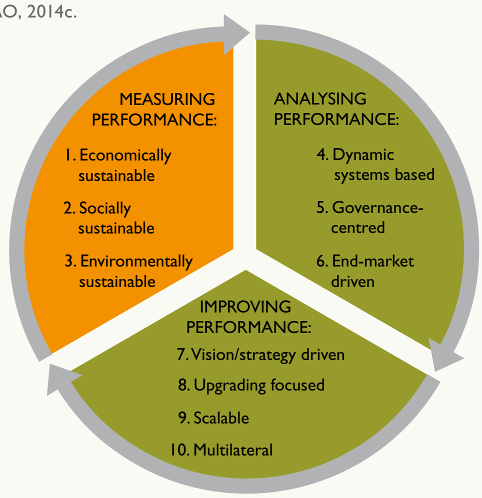
- The third phase is to "improve performance" by following a logical sequence of actions:
    - using the analysis conducted in Phase 2 to develop a specific and realistic vision, and an associated core VC development strategy that stakeholders agree on; and
    - selecting the upgrading activities and multi-lateral partnerships that support the strategy and that can realistically achieve the scale of impact envisioned.

The cycle is then repeated, starting with an impact assessment of the efforts to improve performance.

The CBA of energy technologies outlined in this study informs the first phase of sustainable agrifood VC development: measuring performance.

FIGURE 2.3. Principles of sustainable agrifood value chain development.

Source: Adapted from FAO, 2014c.



2.5. PRO-POOR TECHNOLOGIES

The methodology outlined in this report is particularly suitable to assess pro-poor technologies that address the needs of the most vulnerable people – nearly half of the global population – through investments in "needs-based innovations". They can be described as commercially viable technologies that reduce fossil fuel dependence without lowering productivity whilst responding to the needs of low-income people (UNCTAD, 2011). What differentiates them from true "commercial" technologies is that they are not created, disseminated or marketed with the objective of meeting the demand of a profitable segment of the market, but rather of increasing the quality of life of the most vulnerables. Hence, profit maximization is not the ultimate objective. Examples include energy interventions that improve food preservation and quality, where no quality market premium exists, or certain time-saving interventions.

Commercial technologies used in industrialized countries might not be appropriate for developing countries because they do not necessarily consider the specific needs of the poor and the practical difficulties related to rural life. The links between these pro-poor technologies and improving gender equality are discussed towards the end of the following sub-chapter.

2.6. GENDER-SENSITIVE APPROACH

Rural women face discriminatory attitudes and structural barriers that limit their own and their household's well-being and economic potential. Empirical studies show that women are often less likely to adopt new technology (FAO and IFPRI, 2014) and less able to participate in and benefit from agrifood value chains than men (FAO, 2011b).

The introduction of a new technology in rural communities can therefore alleviate or deepen gender inequalities, at home, in institutions and along a value chain. The impact of a new technology on gender equality is an issue of social justice and could be a determinant of the social sustainability of agrifood value chains.

Gender and value chains

It is widely acknowledged that women are represented disproportionately in lower productivity value chains than men (FAO, 2011a). Milk, vegetables and rice are staple and/or subsistence food products of good nutritional value. Women are highly active in the value chains of these important food products while men dominate in cash crop value chains (e.g. fruits and vegetables for the export market). Moreover, women perform the bulk of subsistence activities outside the value chain.

Within the various value chain nodes, women are more likely to perform lower paid and unpaid work than men and be employees rather than managers. When they do manage value-addition work, it is usually on a smaller-scale than men because there are lower capital barriers to entry (FAO, 2011a), and women still need to undertake burdensome household chores.

Gender and energy

Energy poverty – the lack of access to modern energy services – in poor rural areas affects women in particular, owing to traditional gender roles and responsibilities, as well as to women's limited asset base (IRENA, 2013a). At home, women provide human energy to carry out almost all daily chores, including time-consuming and heavy tasks such as the collection of water, fuel wood and fodder. In off-grid areas, women also spend a high proportion of their income on energy services for household needs compared to their counterparts in developed countries (Glemarec et al., 2016).

Women are generally less able to access energy technologies than men for many reasons including:

- their ability to learn about the technology owing to lower literacy and education levels, less mobility to travel and attend technology demonstrations, more time constraints, lower access to mass media, mobile phones and the internet, lower participation in farmers' associations, and less access to extension services and farmer field schools;

- their ability to acquire the technology itself due to, generally, higher risk aversion, less access to credit, less control over household income and influence over purchases at home, in groups and in the community;

- lower access to, and control over, complementary inputs and services namely land, water, livestock, credit and labour.

The nature of women's lower value and lower productivity work, at home and in value chains, coupled with poorer access to modern energy services than men, has serious consequences. Women work longer hours per day and spend a higher proportion of their time on unpaid, labour-intensive and repetitive tasks than men (FAO, 2015; IFAD, 2016).

Rural women also rely on home- or group-based micro and small enterprises to meet household needs and earn an income, but productivity is often constrained by low access to energy services for lighting, heating, cooking, cooling, mechanical power, etc. (IRENA, 2013a). While these enterprises account for up to as much as 80 percent of employment in some countries, as a group they earn less than ten percent of all income earned and own only one percent of property (Dutta, 2015).

The impact of energy poverty restricts women's time and mobility to undertake more productive and paid work (let alone to rest and for leisure activities) and limits health, productivity, and food and nutrition security in the household and community (IRENA, 2016a).

Recurrent challenges risk worsening the impact of women's energy poverty if access to modern energy services does not improve. For example, increasing natural resource degradation, water scarcity and unpredictable climate shocks are making the existing tasks of water, fuelwood and fodder collection more burdensome as women are forced to travel further afield (UNEP and GRID-Arendal., 2011). In recent years, increased migration from rural areas by the young, able and often male members of households has also added to the farm-related workload of some women who remain (IFAD and FAO, 2008; Paris et al., 2009); although this can also bring the benefit of more freedom to manage work and make decisions (Oucho et al., 2014; Paris et al., 2009).

The situation is compounded when rural women's lack of voice compared to men means that they are not the main decision-makers over energy services (Glemarec et al., 2016) at home, on the farm, or in mixed groups and enterprises. In such cases, the need to invest in energy technologies and services to reduce women's unpaid and/or low productivity work may not be prioritized (IFAD, 2016).

For both rural women and men it is crucial to increase access, adoption and the sustainability of rural energy services at home and in value chains. Furthermore, women's roles and responsibilities at home, on-farm and in micro and small enterprises – and the energy services these require – mean that they know better than most what energy products are needed and how they should perform.

Potential benefits of clean energy technologies for gender equality

The potential benefits of pro-poor clean energy technologies in agrifood value chains in terms of promoting gender equality are mutually reinforcing and include:

- time-savings by women who are time-poor, that is who "work long hours and have no choice to do otherwise" (Bardasi and Wodon, 2009). The time saved can be used to (i) perform other productive tasks to improve household food and nutrition security and/or household income; (ii) participate in training sessions, women's groups, farmers' associations and community meetings that socially empower women – as individuals and collectively – to voice their needs and priorities, and influence their lives; and (iii) for rest and leisure.

- improved health, nutrition and well-being of women and their families owing to less time spent on labour-intensive, heavy and repetitive tasks; and reduced health risks by using cleaner technologies. For example, using biogas instead of traditional biomass or kerosene for cooking reduces many health risks such as burns, poisoning, cancer, and cardiovascular, respiratory and eye diseases caused by indoor air pollution.

- increased income (economic empowerment) from (i) higher sales of agricultural products thanks to improved productivity and reduced food spoilage resulting from upgraded processes that improve cooling, heating or cooking methods; (ii) opportunities to be the owners and managers in value chain nodes such as post-harvest processing; and (iii) employment opportunities for women and men (who may have lost their livelihoods) along agrifood value chains, or in non-farm employment, such as manufacturing, marketing, retailing and servicing energy technologies.

- improved household resilience to food market price shocks due to diversified income streams from employment opportunities for women and men.

- social empowerment of women When women increase the income they earn and control – at home, in institutions and the community – they often have greater influence in decision-making and shaping collective choices. Rural women are also known to invest a greater proportion of their income in the well-being of their families than men (FAO, 2011a).

However, lower adoption rates of new technology by women compared to men mean that the technology may have a neutral effect on gender equality or further reduce women's social, economic and political standing compared to men, with negative repercussions for poverty reduction. To mitigate these risks, this study into clean energy technologies in agrifood value chains includes an analysis of the impact on gender equality.

3. METHODOLOGY

3.1. FEASIBILITY ANALYSIS

A feasability analysis requires sound investigation on various factors as for example the availabiltiy of support services in rural and remote areas. Source: © GIZ/Thomas Imo

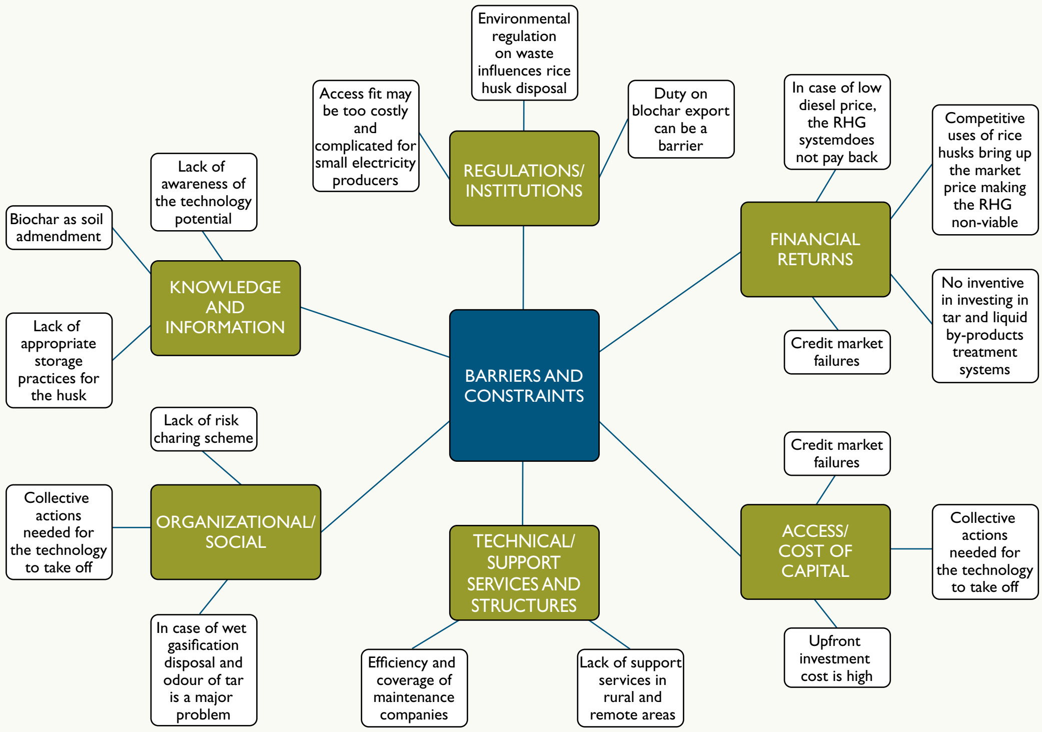
When planning an investment, the operator or project manager should first perform a feasibility analysis (and sometimes a pre-feasibility analysis).[7] This assesses the ability to complete a project successfully, taking into account legal, economic, technological, scheduling and other factors. A feasibility study investigates the possible negative and positive outcomes of a project before investing too much time and money.

The first step is to contextualize the investment into an economic, institutional, social and technical framework. In fact, constraints and challenges to the use of sustainable energy in agricultural and food industries, particularly in developing countries, can stem from these four areas. The main constraints on rice husk supply mobilization and related gasification technology uptake is an example (Figure 3.1). A clear identification of financial, economic, institutional, social and technical opportunities and risks is required as a first screening for the suitability of the investment.

7 In principle, a pre-feasibility study is similar to a feasibility study. The differences are in the level of accuracy and depth of analysis. Pre-feasibility studies offer the fastest method to select the best business scenario, whereas a more in-depth feasibility study offers deeper analysis of the selected scenarios and aims to identify whether the project should be continued or not.

FIGURE 3.1. Possible barriers to rice husk gasification (RHG) as an example of constraints and challenges to sustainable energy uptake.

Source: Authors.



Some of these barriers would be considered in detail in the economic analysis, but an initial identification of constraints to the investment is also necessary during the preliminary feasibility study. In fact, the identification of significant barriers or constraints could make an investment in a specific technology infeasible in a particular environment, even though it would seem financially attractive given an enterprise perspective. Examples of constraints are lack of access to finance; high cost of capital; market failures; network failures; insufficient legal and institutional frameworks; lack of skilled personnel; social, cultural and behavioural factors; geographic constraints; and sustainability concerns.

The adoption of the technology/practice by an entrepreneur or farmer goes through three steps:

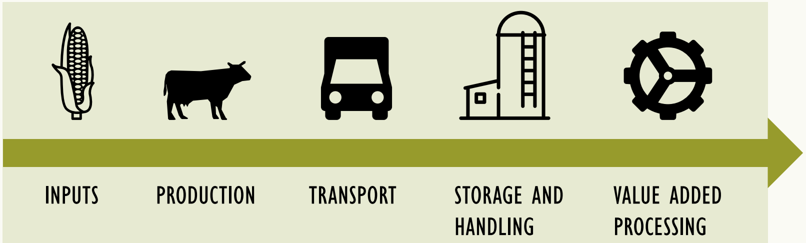
(i) *Awareness* when learning about the technology/practice;
(ii) *Evaluation* by assessing the technology in terms of costs and benefits; and
(iii) *Adoption* by deciding to accept it in full, or modify and adapt it to suit the local situation and any specific needs.

The adoption of the technology depends also on the risk perceived by the individual farmer or business. Therefore, stakeholder dialogue along the value chain in question is important. Weak connectivity between actors, social biases and traditions may represent constraints to the adoption of clean energy technologies.

Renewable energy and energy efficiency interventions can be implemented at various stages along the agrifood value chain, from production to consumption (Figure 3.2). The methodology to perform a feasibility study of the investment is the same, regardless of the technology and value chain stage. The analysis as performed in this report covers potential investments from production to processing but does not consider the retail/consumption stage.

FIGURE 3.2. Examples of reducing fossil fuel inputs by energy efficiency and renewable energy interventions in agrifood value chains.

Source: Authors' elaboration based on REEEP, 2015a.



- Solar, wind-powered water pumping
- Biofuel-powered machines
- Solar desalisation, heating/cooking
- Efficient machinery/maintenance
- Low-pressure, efficient irrigation
- Biomass residues energy generation

- Efficient refrigeration vehicles
- Solar, geothermal food drying for storage
- Solar cooling and refrigeration
- Minimized/efficient packaging
- Food loss reduction
- Efficient drying
- Improved insulation for cold storage

- Solar, wind, hydro milling, processing, cooking, drying etc.
- Renewable electricity and heating application
- Modern biomass for cooking
- Efficient processing for cooking
- Smart integration into existing fossil-fuel based power system

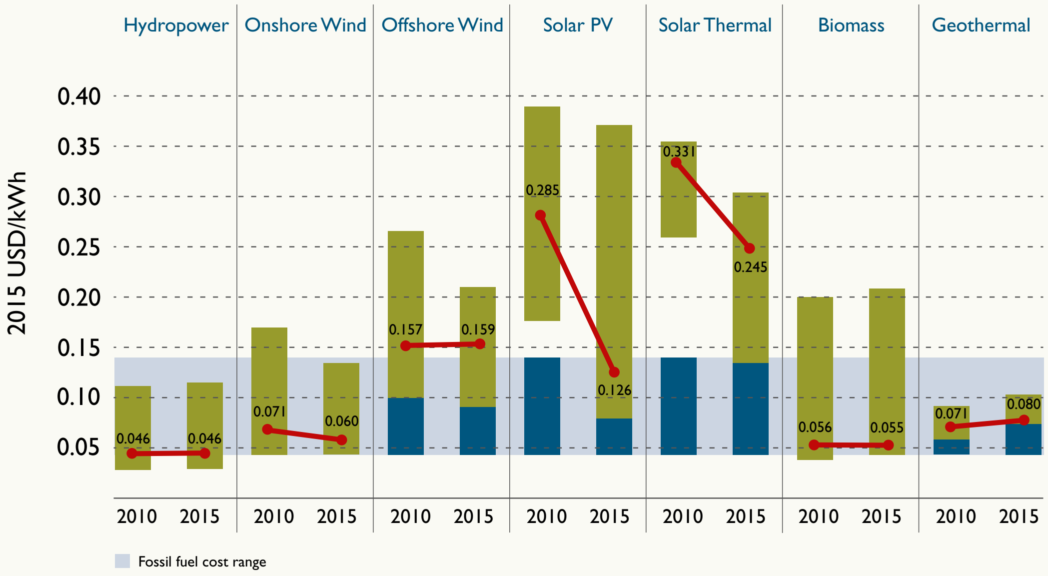
Analysis from many demonstration and commercial renewable energy plants show that costs of projects are very site-specific. However, in many locations, the levelized costs[8] of renewable energy technologies are becoming more competitive with the average costs of fossil fuel-fired thermal electricity, heat and transport fuels. Moreover, the costs for renewable energy technologies are declining as the size of their markets is increasing (Figure 3.3). For example, in remote rural regions with no access to an electricity grid, autonomous renewable energy systems are already competitive as they avoid expensive grid connection costs, or can displace costly diesel generator systems.

8 The levelized cost of energy (LCOE) represents the cost of an energy-generating system over its lifetime. LCOE is often cited as a convenient indicator of the overall competiveness of different generating technologies. It is calculated as the per unit price at which energy must be generated from a specific source over its lifetime to break even (recover all costs, including financing and an assumed return on investment). It usually includes all private costs that accrue upstream in the value chain, but does not include the downstream costs of delivery to the final customer, the cost of integration, or external environmental or other costs. Subsidies and tax credits are also not included.

FIGURE 3.3. Trend in global renewable energy levelized cost of electricity, 2010–2015.

Note: The green bars represent ranges and red bars indicate weighted averages.

Source: IRENA, 2016a.



3.2. COST-BENEFIT ANALYSIS

The attractiveness of an investment in clean energy solutions must be assessed by a financial and economic analysis.
Source: © GIZ/Lucas Wahl

In order to quantitatively assess the attractiveness of an investment in sustainable energy, a financial and economic analysis (FEA) needs to be performed. The main goal of the initial financial analysis is to examine the financial returns to project stakeholders. A financial analysis provides the foundation for an economic analysis, which is carried out to ascertain a project's desirability in terms of its net contribution to the economic and social welfare of the country (or sub-national entities) as a whole.[9] In development studies, the terms "financial" and "economic" are commonly defined as follows:

- financial analysis is undertaken from the perspective of individual agents or categories of agent (farmers, retail traders, primary assemblers, food processors) and includes the analysis of production-utilization accounts, profitability of investments, etc.; and

- economic analysis is undertaken from the perspective of the overall economic system (national economy, sector or chain) or large groups of heterogeneous agents and includes the analysis of taxes, subsidies, etc. and environmental and social externalities.

The financial and economic CBA therefore consists of two main steps:

(i) Financial cost-benefit analysis: an assessment of the financial profitability and sustainability of an investment in order to determine whether farmers and other stakeholders have sufficient incentive to participate;

(ii) Economic cost-benefit analysis: an assessment of the economic viability of a project from the point of view of the national (or sub-national) economy. This step should also examine the expected impact on the government budget to ensure fiscal sustainability. Furthermore, the economic analysis of investments in renewable energy usually includes an assessment of a project's impact on social and environmental aspects.

In agricultural and food enterprises, renewable energy technologies are adopted as substitutes to traditional energy technologies, usually fossil fuel-based, or to manual labour. Therefore, the financial and economic analysis of the investment requires a comparison with these benchmarks. The FEA of an investment is concerned with the incremental costs and benefits, and therefore requires a comparison between the potential situations with and without the project being developed.

The first step is the identification and description of both the benchmark scenario (which normally consists of fossil fuel-powered and/or inefficient or ineffective technologies) and the post-energy intervention scenario (in which the advanced technology is adopted). For instance, an intervention introducing solar photovoltaic (PV) technology to pump water for irrigation could consider a diesel engine-powered pump or a grid electricity-powered pump as the benchmark scenario. The financial analysis of an investment in the PV pump would require the comparison between two

9 For more information, see: http://www.fao.org/investment-learning-platform/themes-and-tasks/financial-economic-analysis/en/.

scenarios. For an off-grid PV irrigation system, the benchmark is typically diesel-powered water pumping.

The second step is the identification of the outcomes of the investment including the capital and operating costs and the monetized benefits. This is particularly important for renewable energy interventions since the initial capital costs are typically high. Since costs and benefits do not occur at the same time – with costs generally preceding and exceeding benefits during the early years of the investment – the comparison requires discounting techniques. Lifecycle costs include the equipment capital costs, operation and maintenance (O&M) costs and fuel costs. Methods of discounted cash flow analysis are applied whereby all future costs and benefits are converted into current amounts (present values) via a constant discount rate (Kelley et al., 2010).

The third step is to determine incremental net flows (financial and/or economic) that result from comparing costs and benefits of the technology option with the benchmark scenario. With these elements, it is possible to calculate the corresponding profitability indicators.

BOX 1. CHOICE OF DISCOUNT RATE.

Many aspects must be considered when choosing an appropriate discount rate for CBA. First, a distinction should be made between the financial discount rate, reflecting the opportunity cost of capital for private investors, and the social discount rate, revealing society's relative valuation on today's well-being versus well-being in the future.

Several approaches can be adopted to choose a discount rate. For instance, the discount rate can reflect the time value of money; the marginal opportunity cost of capital; the weighted average cost of capital (WACC); or the shadow price of capital (ADB, 2007). In general, when choosing an appropriate discount rate for investment in the agrifood sector, the main factors are: interest rate of 10-year government bonds; commercial lending rates; borrowing interest rate; the central bank's official interest rate; deposit interest rates; the WACC for agriculture or the agrifood sector; and a specific country-risk premium.

Further data on cost of capital and risks specific to the sector should be accounted for, if available. In some cases, technology-specific risk premiums can be taken into account. For instance, projects involving large plants are riskier than smaller systems and energy efficiency interventions, so they can have a higher discount rate. Sources of information for these data can be the World Bank, the country's Central Bank, the International Monetary Fund (IMF) and other national and international statistics.

Selecting a financial discount rate to assess investments from the perspective of a private investor is different than selecting the economic discount rate to assess investment projects from the perspective of a country, region or society. A country will probably borrow at a lower cost than the private sector. In particular, when considering adaptation measures, a high discount rate can underestimate the potential value of a long-term climate adaptation investment for the well-being of future generations.

Still, in the context of the case studies selected for this report, for simplicity, we used the same discount rate for the economic CBA and the financial CBA (which depends only on the characteristics of the country where the investment takes place).

3.2.1. FINANCIAL COST-BENEFIT ANALYSIS

A CBA consists of monetizing all major benefits and all costs generated by the investment and presenting their streams over the lifetime of the technology, usually expressed in number of years (cash flow). Costs and benefits can be directly compared (i) between different scenarios and (ii) with reasonable alternatives to the proposed energy intervention. At this stage, how the agents finance their investment is not considered and, for simplicity, it is assumed that they have the capital needed to cover the investment costs and do not make use of financial markets. In the second phase of the CBA this assumption is dropped and the role of financial instruments in the adoption of the technology is analysed.

Generally speaking, an energy intervention is considered "viable" if the sum of expected incremental benefits is larger than the sum of all costs accrued in implementation. This can be assessed through profitability indicators. In general, CBA provides four main indicators: the net present value (NPV), the internal rate of return (IRR), the benefit/cost (B/C) ratio and the payback time (PBT). These indicators assess attractiveness of investments by comparing the present value of money to the value of money in the future, taking into account the time value of money (discount rate) and returns on investment. Therefore, they are important decision-making tools for investors, national governments, as well as for donors and international financial institutions (IFIs).

The NPV indicator is determined by calculating the costs (negative cash flows) and benefits (positive cash flows) for each period of an investment and discounting their value over a periodic rate of return. The NPV is defined as the sum that results when the initial costs of the investment are deducted from the discounted value of the net benefits (revenue minus cost).

NPV EQUATION

$$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} + R_0$$

Where

R_t is the sum of all the discounted future cash flows

R_0 is the (negative) cash flow at time zero, representing the initial investment

t is the time of the cash flow, depending on the project lifetime

i is the discount rate or rate of return

Therefore, the NPV of an investment (or a project) depends on its net benefits, its lifetime and the discount rate. Whenever the NPV is positive (NPV > 0), the investment is considered worthwhile or profitable. Comparing the NPVs of several possible investments allows for the identification of the alternative that yields the highest result – for cases in which the alternatives are mutually exclusive. Among mutually exclusive projects, the one with the highest NPV should be chosen.

The **IRR** indicator is defined as the discount rate at which the NPV equals zero. This rate means that the present value of the positive cash flows for the project would equal the present value of its costs. If the IRR exceeds the cost of capital, the investment is profitable. For a project to be profitable, the IRR has to be greater than the interest rate that could be earned in alternative investments or than the opportunity costs of capital (*r*). Therefore, when IRR > *r* the investment is considered viable.

NPV and IRR are calculated on the same project cash flows of incremental net benefits. However, when the choice is between two alternative interventions with differences in the scale of investment, the IRR should not be used. In fact, the NPV is preferable when the investors set their goals in absolute terms, since it ensures that the operator reaches an optimal scale of investment in those same terms, while the IRR expresses the return in percentage. For example, a project with an IRR of 500 percent on US$1 is less attractive than a project with an IRR of 20 percent on US$100, although the former has a higher IRR. Moreover, calculating the IRR is not possible when the flow of net incremental benefits does not have a negative element.

The **B/C ratio** indicator is the ratio of the present value of benefits to the present value of costs over the project lifetime. The B/C ratio provides some advantages when a ranking of alternative investment projects is needed under budget constraints. If B/C ≥ 1 the project is accepted; if B/C < 1 the project is not profitable.

The **PBT** measures the time required for the net cash inflows to equal the original capital outlay. It is the number of years required for the discounted sum of annual savings to equal the discounted investment costs; or in other words, the timespan after which the investment will start to pay back. It does not reflect the magnitude of the investment and, unlike the other indicators, it expresses the profitability of the investment in terms of time. Between two alternative projects, the investor is likely to choose the one with the shorter payback period.

From the perspective of a private stakeholder (financial analysis) participating in the investment with risk capital, the wealth created by a project is defined as the financial NPV. In financial analyses, all costs and benefits should be valued at market prices. Only cash inflows and outflows are considered (depreciation, reserves and other accounting items not corresponding to actual flows are excluded).

BOX 2. STEPS IN FINANCIAL CBA.

(i) Identify benefits and costs for both investment and benchmark scenarios for their lifetime.

(ii) Select an appropriate discount rate to calculate discounted flows. Deduct the discounted flows of costs from the discounted flows of benefits to obtain the discounted net benefits of the proposed interventions and of the benchmark scenario.

(iii) Calculate the differences between the project and benchmark scenario net benefits in order to determine the net incremental benefits of the proposed interventions.

(iv) Calculate the project's financial profitability indicators of each scenario (i.e. financial NPV, financial IRR, B/C ratio, and PBT), and apply these investment criteria to make an investment decision (positive or negative).

Table 3.1 summarizes the items to be considered and calculated when performing a CBA of energy technologies for the agrifood sector, while Figure 3.4. synthesizes the logical steps of a CBA. Supplementary online support tools that farmers and food processors can adopt to perform CBA and value chain analyses are presented in Box 4. These tools can help performing the CBA as illustrated thus far but do not include the assessment of externalities and co-benefits described in Section 3.3.

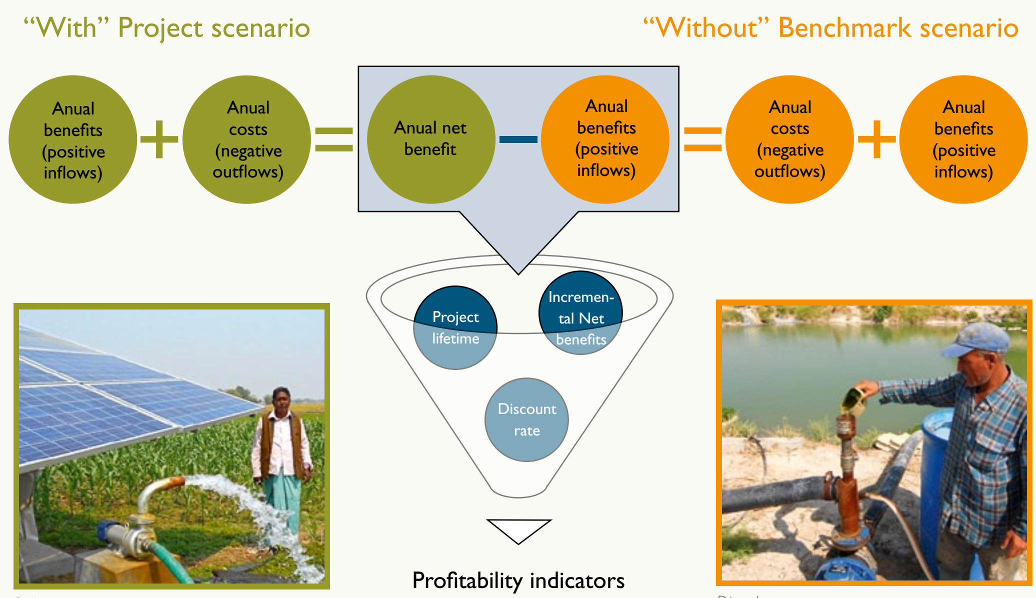
TABLE 3.1. Items to be considered in a financial CBA of energy technologies.

	Items	Unit	Benchmark scenario	Investment scenario
t	Life	year	n	n
a	Capital cost (Including installation cost)	$$	a_0	a_i
b	Maintenance cost	$$/year	b_0	b_i
c	Operating cost (labour, fuel, inputs, etc.)	$$/year	c_0	c_i
C	Total costs	$$/year	$C_0 = a_0 + b_0 + c_0$	$C_i = a_i + b_i + c_i$
d	Benefits (outputs)	$$/year	d_0	d_i
e	Discount rate	%	e	
f	Discounted costs	$$	$f_0 = \frac{C_0}{(1+e)^n}$	$f_i = \frac{C_i}{(1+e)^n}$
g	Discounted benefits	$$	$g_0 = \frac{d_0}{(1+e)^n}$	$g_i = \frac{d_i}{(1+e)^n}$
h	Discounted net benefits	$$	$h_0 = g_0 - f_0$	$h_i = g_i - f_i$
i	Incremental discounted net benefits	$$/year	$i = h_i - h_0$	
	NPV	$$	$\sum_{n=0}^{N} \frac{i_t}{(1+e)^n}$	

Source: Authors.

FIGURE 3.4. Summary of main steps in the cost-benefit analysis.

Source: right: Claro Energy; left: Jörg Böthling.



Solar pump.

Diesel pump.

3.2.2. ECONOMIC COST-BENEFIT ANALYSIS

The basic principles for carrying out financial and economic analysis are the same and both are required for project screening and selection. However, the financial analysis deals with the cost and benefit flows from the point of view of the investor, farmer or food processor (in our case), while the economic analysis deals with the costs and benefits to society. An enterprise is interested in financial profitability and sustainability, while society is concerned with wider objectives, such as social and environmental issues, and net benefits to society as a whole.

The main differences between financial and economic analysis are that the economic analysis.[10]

(i) Attempts to quantify "externalities", i.e. negative or positive effects on specific groups in society without the project entity incurring a corresponding monetary cost or enjoying a monetary benefit. This includes both environmental and socio-economic impacts resulting from the energy intervention. If the environmental and socio-economic (positive or negative) impacts are monetized and borne by the agent(s) performing the investment, they should be included in the financial CBA. Still, if these impacts take place at different stages of the value chains and are not internalized by the operator, they should be included in the economic CBA.

(ii) Removes transfer payments, i.e. subsidies, direct or indirect support to producers or other actors, fiscal incentives (tax credits, deductions and exemptions), etc.

(iii) Makes use of "shadow prices" that might differ from the "market prices", which reflect the effective opportunity costs for the economy, thus achieving a proper valuation of economic costs and benefits from the perspective of the economy as a whole. For example, the shadow price for electricity produced from coal also considers the impact/social cost of coal burning on the environment (which is not included in the market price).

An economic analysis takes into account energy subsidies and taxes, the impacts of the energy intervention on land, labour and human rights, local peoples' livelihoods, environment, GHG emissions, etc. (FAO and USAID, 2015). The basic aim of the economic analysis of an investment project is to provide information to decision makers as to the expected contribution of the project to society's welfare (ADB, 2015). The economic CBA provides a means to identify, quantify, and, wherever possible, value all impacts of the intervention, including relevant social and environmental impacts.

Externalities and co-benefits are context-specific and can be inserted in the analysis in order to modify the structure of economic costs and benefits of the project. These include for example economic incentives to renewables or fossil fuels; costs to mitigate climate change or to ensure the more efficient use of energy, water and land; costs

10 For more information visit the FAO Investment Learning Platform at http://www.fao.org/investment-learning-platform/themes-and-tasks/financial-economic-analysis/en/.

accrued in the treatment of water; measures to contain negative environmental impact, etc. (see also Section 3.3). Even though these are all important aspects of a project, they are often not included in the financial investor business plan.

As in the financial CBA, costs and benefits of the energy intervention must be (i) compared with the benchmark scenario to obtain incremental flows, and (ii) discounted to take into account opportunity costs of capital.

BOX 3. STEPS IN FINANCIAL CBA.

1. Convert all market prices into economic/shadow prices that better reflect the social opportunity benefits and costs of the investment. This can be done by:
   a. Removing transfer payments: taxes and subsidies on fossil fuel or renewable energy technology, import duties, taxes or subsidies on intermediate inputs or final outputs. Subsidies and financial incentives are paid with public money; therefore they are a cost for society. On the other hand, taxes and other duties represent a revenue for the state, and therefore are counted as benefits for society.
   b. Quantifying externalities (positive and negative) not borne by the investor(s): some of the impacts on environmental and socio-economic dimensions can be monetized (Table 3.2) and added as a cost or benefit in the economic CBA. Positive impacts and avoided costs are recorded as benefits, while additional negative outcomes represent a cost for society.
2. Compare the project's costs and benefits with the benchmark scenario to obtain the project's incremental net flows.
3. Calculate the economic performance indicators (if possible, adopting a social discount rate): economic NPV, economic IRR, economic B/C ratio and PBT.
4. If useful, perform a sensitivity analysis in order to understand the main risks and uncertainties that could affect the proposed project (see Section 3.4).

BOX 4. SOFTWARE FOR COST-BENEFIT AND VALUE CHAIN ANALYSIS.

CBA can be unfriendly for a non-professional audience. Several free tools are available to support cost-benefit evaluations of energy interventions, including the FAO Value Chain Analysis (VCA) tool or the FAO WinDASI tool.

The VCA Tool assesses socio-economic and environmental policy impacts. The data components of the tool defining the economic content of the chain are:

- commodities and services (e.g. seeds, taxes, wheat, energy, labour);
- activities (such as commodity production, processing and trading); and
- plans (an agent, or a group of agents, a geographical area or an exploitation method).

The software allows building a baseline scenario, which corresponds to a benchmark situation, and generating policy measures or changes in the value chain that automatically modify the original reference scenario (FAO, 2012b). It also allows the creation of different scenarios in order to analyse the socio-economic impact of various policies, such as the adoption of new low-carbon energy efficient technologies or support for renewable energy. The information about how inputs and outputs would change before and after the intervention is exogenous and can come from other sources. Focusing specifically on the VCA, the tool allows for:

- commodity chain analysis;
- financial analysis;
- impact analysis using market or shadow prices;
- scenarios comparison; and
- measurement of competitiveness and profitability indicators.

WinDASI is a software for CBA of specific investment projects. After cost and benefit data are inserted in the database, the software guides the user how to calculate:

- flows of physical quantities of outputs, inputs and investment items;
- flows of current, discounted and cumulative costs, benefits, and net benefits;
- flows of incremental (with vs. without project) current, discounted and cumulative net benefits; and
- project indicators such as NPV, IRR, B/C and sensitivity analysis.

Calculations can be carried out at different levels of aggregation for the different components of an investment project (i.e. plans, zones and projects). In addition, WinDASI allows for calculation and comparisons of different scenarios (with project versus without project). However, this software does not have a value-chain approach.

Both softwares can help the investor assessing the financial CBA of the energy intervention, but they do not provide guidance on which economic, social and environmental factors should be included in the analysis. This is what the methodology presented in this section aims to do.

Introducing clean energy technologies in agrifood chains potentially results in impacts regarding environmental or socio-economic externalities (Table 3.2). If these can be monetized they are to be included in the economic CBA as illustrated above. However, it is not always possible to monetize such environmental or socio-economic externalities and therefore a more descriptive analysis may be needed, using qualitative or quantitative impact indicators expressed in biophysical terms.[11] The latter are illustrated and described in Section 3.3.

TABLE 3.2. Items to consider in an economic CBA of energy technologies.

Items		Short description
Financial net benefits		Incremental net benefits resulting from the financial CBA.
Taxes		Taxes on intermediate inputs or final outputs and duties on imported goods represent a revenue for the government, and therefore are monetized as benefits in the economic CBA.
Subsidies		Subsidies and financial incentives on intermediate inputs or final outputs represent negative flows for the government, and therefore are counted as costs in the economic CBA.
Value added along the value chain		The value added in each step of the value chain is measured as the difference between the value of the output and the cost of the inputs. An energy intervention in a specific stage of the value chain can generate positive or negative impacts on the value added as created at previous or subsequent steps of the VC. For instance, the introduction of a cold storage technology (at the storage stage) that reduces food waste, may also increase value added in production, transport and processing stages.
Environmental externalities	Productivity increase due to soil quality	Energy interventions that indirectly improve (or worsen) soil quality can generate an increase (or decrease) in productivity, which would result in higher (or lower) values for agricultural production throughout the value chain. This benefit (or cost) can be monetized at farmer or market prices (depending on the destination of the product in the specific context) and are introduced in the economic analysis if not already accounted for in the financial CBA.
	Change in amount of fertilizers used	Energy interventions may impact the amount of chemical fertilizer applied throughout the value chain. The amount used can be monetized by applying the local price of fertilizer in the intervention area. If it was not accounted for in the financial CBA, a reduction in fertilizer use will result in a monetary benefit for the society, whilst an increase would be recorded as a cost.
	Health cost due to indoor air pollution	The introduction of energy technologies can reduce health hazards associated with indoor air pollution from the use of fuelwood, charcoal, kerosene and other fossil fuels. If these health benefits also affect individuals other than the investor(s), and whenever avoided medical expenses connected with illnesses (such as pneumonia, strokes, heart diseases, chronic obstructive pulmonary disease, asthma, blindness and cancer) can be monetized, they can be included in the economic CBA as a benefit for society.
	Change in the cost of water used	Energy interventions may have an impact on water used along the value chain. If a monetary value can be applied to the additional water demanded (or saved), this can be included in the analysis as a cost (or benefit) on society (if it was not reported in the financial CBA). The market price of water (if any) could be used as an indicator of its value at this stage, provided that the analysis will be complemented with the aspects underlined in the "water use and quality" indicator in Section 3.3.

11 Alternatively, some of these externalities can be measured using the "willingness to pay" of consumers.

	Cost due to water quality treatment	If an energy intervention contributes to an increase (or decrease) of water pollution along the value chain, the additional (or avoided) cost of water treatment or purification can be monetized as input in the CBA. In absence of strict regulations on water quality, few private investors would take into account this externality and therefore would not include it as a cost (or benefit) of their investment. Therefore, it is often borne by society.
	Additional income due to food wastage avoided	Several energy interventions can help reduce food wastage and spoilage, thus increasing the value added at different stages along the value chains. This increase in value can be due to improved food quality, additional quantity, or both. Avoidance of food wastage can be reflected by additional monetary revenues from having a higher quality or bigger quantities of the produce (if these were not accounted for in the financial CBA).
	Value of GHG emissions saved	Energy interventions usually aim to reduce GHG emissions. GHG emissions avoided (in terms of CO_2eq) can be monetized (for example in the cap-and-trade system set up to meet the obligations specified by the Kyoto Protocol) if they were not accounted for in the financial CBA. Avoided emissions can be reported as benefits (or avoided cost) for society. A large range of estimates of social costs of avoided GHG emissions exists in the literature.[13] In this study, a social cost of carbon (SCC) of US$36/tonne of CO_2eq emitted was assumed.
Socio-economic externalities	Additional income due to increased access to energy	As fossil fuels and electricity bills often constitute a large share of household expenditure, the introduction of alternative energy sources (e.g. renewable sources, biomass co-products or crop residues) can allow households to save money. This is a financial benefit if there is no spillover effect for society, such as increased access to energy beyond the economic agent.
	Household income	As indicated in the "household income" indicator (in Section 3.3), changes in income may derive from: • change in wages; • increase (or decrease) in revenue from the sales of the product due to higher (or lower) quality or quantities sold; • savings on energy purchases and other agricultural inputs; and • diversification of the sources of income. If these changes have been already monetized in the financial analysis or under other environmental or social impacts (e.g. change in soil quality, fertilizer use, waste reduction, additional income related to energy access, etc.), they should not be included again in this stage to avoid double-counting. Only the income components not already considered in other items should be included as a cost or benefit at this stage.
	Additional time saved for productive activity	The introduction of energy technologies may reduce the time spent on collecting fuelwood, making charcoal, or delivering water. This saved time can be spent on other activities including education, leisure or household activities. If the time is spent in alternative productive activities, it can be monetized by multiplying the hours saved by an average hourly rate for the agricultural service appropriate to the context. The time spent on "collection" activities is thus considered an opportunity cost because the farmer could have spent those hours in another income-generating productive activity. The opportunity cost of time should be included in the financial analysis if it is saved by the household investing in the technology. Otherwise, it will be included in the economic analysis i.e. if the activities displaced were performed by individuals other than those in the household.

12 Yohe et al. (2007) summarize the literature on SCC estimates: peer-reviewed estimates of the SCC for 2005 had an average value of US$12/t$CO_2$. The US federal government has had an official estimate of the SCC since 2010. In 2015, it was US$36/t$CO_2$ with a three percent average discount rate (EPA, 2016).

	Labour remuneration	Energy interventions may contribute to creating employment (or unemployment) along the value chain. Traditional jobs may be displaced by the introduction of a new technology, which becomes a societal cost if a greater number of new employment opportunities are not created. The "employment" indicator (outlined in Section 3.3) explains the steps of the value chain and the phases of technology deployment that can be affected by an energy intervention. If throughout the value chain data on the wages corresponding to a job created (or destroyed) can be found, the net change in remuneration due to the introduction of the technology can be monetized and included in the economic CBA.

Source: Authors.

3.3. EXTERNALITIES AND CO-BENEFITS

Effective such as solar powered drip irrigation can save labour and increase water use efficiency resulting in higher productivity.
Source: © Jörg Boethling/visualindia

This section provides an introduction into externalities and co-benefits before presenting the 12 indicators in detail in paragraphs 3.3.1 and 3.3.2.

So far in the analysis monetized costs and benefits of energy interventions in agrifoood chains have been introduced. The difficulty arises when a non-financial input has to be counted. In addition to financial change, social and environmental changes induced by the new technology need to be considered. Both quantitative and qualitative information are included in the analysis, whereby qualitative data might require some interpretation or judgement.[13]

BOX 5. GENDER-RELATED EXTERNALITIES AND CO-BENEFITS.

Externalities and co-benefits from access, adoption and sustainability of clean energy technologies also affect gender issues. Such gender-related aspects are reflected in the impact indicators of the economic CBA (where relevant and given data availability), see Table 3.2. In particular:

- Women and men's access to: information about the technology; the acquisition of the technology itself; and control of complementary inputs and services;
- How women and men's adoption is affected by: the appropriateness of the technology for their needs; the acceptability of the technology in the socio-cultural setting; and their role/ability to participate in rural institutions;
- How sustainability is determined by:
  - Social empowerment: the ability of women and men to influence and make decisions at home, in groups, at work and in the community.
  - Economic empowerment: the ability of women and men to generate an income by using the technology. This also includes looking at the risk of husbands and male members of groups taking control from women of profitable technologies/activities and/or the income generated from them. For example, in developing countries up to 45 percent of the poorest women have no say in decisions about how their own income is spent (IFAD, 2012).
  - Access to training and services by women and men for O&M of the technology and the ability of both genders to cover the associated costs.

Other important gender issues related to the sustainability of technologies, include: women's and men's participation in technology development and priority setting at the local, national and sectoral (agriculture, science and technology) level; and an enabling environment (including an institutional and policy framework) conducive to gender equality in clean energy services, poverty reduction and pro-poor economic growth.

A range of 12 impact indicators was developed to assess potential non-monetized environmental and socio-economic impacts that could arise when introducing an innovative clean energy technology (Table ES.1). These indicators (below) can be used to assess the environmental and socio-economic impacts of the selected energy technologies as outlined in Section 4. They show the relevance of an energy intervention for sustainability issues by identifying the potential impacts. The descriptions focus on the three specific value chains: milk, vegetables, and rice. The involvement of all stakeholders is important to identify and describe the impacts of the investments. Interview surveys may be used to seek opinions about such impacts.

13 Further framework and examples can be found in the IRENA report "Renewable Energy Benefits: Decentralised solutions in agri-food chain" (2016) available at http://www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=36&CatID=141&SubcatID=3746. Quantitative analysis of the impact of renewables in general can be found in the IRENA report "Renewable Energy Benefits: Measuring the economics" (2016), available at http://www.irena.org/DocumentDownloads/Publications/IRENA_Measuring-the-Economics_2016.pdf.

Food security is not addressed by a distinct indicator since the following four dimensions of food security are covered by the other 12 indicators:

- Food availability is linked to soil quality and land requirement, which influence agricultural yield and production, and reduction of food losses, which increases food supply;
- Economic and physical access to safe and nutritious food is impacted by improved household income (including additional revenues related to access to energy);
- Food utilization is related to access to energy for clean cooking; and
- Stability of the three above dimensions over time is associated with employment creation and improved household income.

3.3.1. ENVIRONMENTAL IMPACTS

Energy interventions can have adverse impacts on natural resources not expressly under consideration, such as soil quality in the case of biomass removal, groundwater quality in the case of geothermal energy generation, downstream users in the case of mini-hydro power, and irrigation including solar or wind-powered water pumping (FAO and USAID, 2015). The sustainability indicators of environmental impacts illustrated below do not assess the sustainability of specific energy interventions since they would require a description of the socio-economic and biophysical characteristics of the context. Rather, they highlight the change in resource availability due to an intervention.

This section introduces some indicators that can help measure environmental impacts.

INDICATOR: SOIL QUALITY

Indicator description: Change in soil quality, in particular in terms of soil organic carbon (SOC);

Measurement unit: grams/m^3 of soil (for SOC);

Directionality: The impact is positive if the indicator increases;

Relevance to sustainability: To assess the impact on soil quality, it is necessary to address the effects of an energy intervention on five key aspects that contribute to soil degradation (FAO, 2011c):

(i) loss of soil organic matter (SOM), leading to decreased carbon and soil fertility;

(ii) soil erosion, leading to soil loss (especially of fertile topsoil);

(iii) soil salinization, due to accumulation in soils of mineral salts from irrigation water and/or inadequate drainage;

(iv) soil compaction, reducing water infiltration and storage, and limiting root growth; and

(v) loss of plant nutrients, e.g. through intensive harvesting.

(vi) These factors are often interlinked, and not all technologies will affect all of these aspects.

Energy interventions which involve the co-production of organic wastes that can be returned to the soil (typically from bioenergy applications such as biogas digestate or ash from woody biomass combustion) can have an impact on soil nutrient status, quality, and fertility. Technologies that involve a change in agricultural practices, such as irrigation, can also have an impact on soil quality.

In the milk value chain, biogas technologies requiring manure as feedstock can reduce the quantity of manure left on pasture, which can have an impact on soil quality and nutrient content. SOM (i) maintains nutrient capital such as nitrogen, phosphorus, sulphur and iron; (ii) improves soil structure; (iii) minimizes erosion; and (iv) helps water infiltration and retention.

Liquid effluent and organic digestate slurry produced by the anaerobic digestion process can either be used as a soil improver without further pre-treatment, or be further processed to yield a compost for use in horticulture and landscape activities as a soil conditioner. Applying these organic by-products to the soil can reduce the potential for wind and water erosion, and improve productivity by increasing SOM and by supplying additional nutrients (Waste & Resources Action Programme, 2009).

In rural areas, resource-poor or subsistence farmers, in particular women, commonly produce crops on poorer soils, on less land, and with fewer or zero inputs and services than commercial farmers. The on-site and free supply of organic fertilizer from a biogas digester therefore represents two significant opportunities for subsistence farmers. One option is to apply the fertilizer to their land to improve soil productivity and fertility, and to ultimately increase household food security. Alternatively, some or all of the organic fertilizer could be bagged and sold at the local market, foregoing improvements to the farmer's soil but increasing and diversifying household income.

The extent to which women reap the benefits of improved soil quality and how gender equality is promoted depends on many factors, including:

- land tenure security, which is often lower for women than men and influences the motivation to invest resources in improving soil productivity;
- ownership: on whose crops/land the organic fertilizer is applied, for example on staple crops or kitchen gardens managed by women, or on cash crops cultivated by men;

- task allocation: who is responsible for applying the fertilizer to the fields and how long this takes; and

- distribution of benefits: how the benefits of improved yields in the long term, such as food security, income, returns to labour, are distributed.

In areas with high average temperatures, water evaporates more quickly and mineral salts accumulate (salinization) with adverse effects on plant growth. This can be exacerbated by irrigation systems and/or inadequate drainage. Both women and men involved in operating irrigation systems need equal access to training and extension services on appropriate irrigation techniques to prevent this from happening.

Moreover, the removal or burning of plant residues typically left on the ground after harvesting (such as rice or cereal straw) for bioenergy use or leaves the soil without adequate protection to surface erosion by rainfall and wind, resulting in loss of SOM.

Method and limitations: SOC is commonly used as an indicator to assess soil quality and potential crop productivity. SOC levels can be compared before and after an intervention through methods such as adding the digestate by-product from an anaerobic digester. Ideally, this indicator would require repeated measurement of SOC content from each production area, following established methods like the Soil Sampling Protocol for Soil Organic Matter (European Commission, 2011) or the Natural Resources Conservation Service Soil Survey Laboratory Methods Manual (USDA, 2004). Methods and sampling should be consistent over time and eventually be taken at intervals that are relevant to the rotation cycle of the crop.

Both laboratory and in-situ methods can be used to measure SOC levels if the scale of the intervention permits (FAO, 2016a; USDA, 2009). When laboratory tests cannot be applied, the FAO Visual Soil Assessment method may provide a useful alternative for estimating soil quality before and after the intervention. If the SOC levels decline, it might be useful to investigate the extent to which the technology introduced could be responsible.

Effective in-situ measurements require intensive and carefully designed sampling, so these may be infeasible due to limitations in the capacity and resources available. Moreover, the soil quality indicator should be re-measured at appropriate intervals between one to 5 years depending on the soil type, crops grown, likely impacts, and rates of impact (FAO, 2011c). Ideally, the baseline year data for the measurement should be known before the energy technology is adopted, or if such data do not exist, then the data from the first year available will have to be used.

Possible data sources: This indicator usually requires field measurements for specific locations.

Relevance to SDGs: This indicator is relevant for **Goal 2** "End hunger, achieve food security and improved nutrition and promote sustainable agriculture", in particular **Target 2.4; Goal 12** "Ensure sustainable consumption and production patterns", in particular **Target 12.4;** as well as **Goal 15** "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss", in particular **Target 15.3.**

INDICATOR: FERTILIZER USE AND EFFICIENCY

Indicator description: Change in (i) the amount of chemical fertilizer applied and (ii) partial factor productivity (PFP);

Measurement unit: (i) kg of nutrient and (ii) crop yield per unit of nutrient applied;

Directionality: The impact is positive if (i) decreases and/or if (ii) increases;

Relevance to sustainability: This indicator is relevant to technologies involving fertilizer use and/or that generate by-products that can replace or displace fertilizer use. For instance, in the case of biogas production, the digestate (slurry) is a by-product that can be used as a fertilizer and soil conditioner.

Inorganic fertilizer consists mainly of nitrogen (N), phosphorus (P) and potassium (K) macro-nutrients. Fertilizer use and efficiency vary widely according to region, soil and crop. Average annual N, P, K applications range from zero in sub-Saharan Africa to 500 kg/ha, 50 kg/ha, and 100 kg/ha respectively in double-cropped Chinese rice fields (Smil, 2008).

This indicator measures any change in fertilizer use and efficiency. For instance, in the case of biogas used for milk cooling in an integrated farming system, the introduction of the slurry by-product is expected to decrease or offset the application of chemical fertilizers.

Fertilizer efficiency shows great variability. For instance, N uptake by crops tends to be particularly inefficient. In intensive rice production, a substantial part of the nitrogen applied is lost through leaching, denitrification and – as ammonia (NH_3) – leading to water pollution, decreasing soil productivity, and GHG emissions (FAO and USAID, 2015). Inefficient fertilizer use does not only cost money but also can cause water, soil, and environmental pollution.[14]

Method and limitations: Fertilizer use can be measured through a comparison with the benchmark scenario. Annual N, P and K loadings from fertilizer can be expressed as kg of N, P and K nutrients applied (for a given area and cultivation) per year.

Fertilizer efficiency can be measured by the PFP, a simple production efficiency expression calculated in units of crop yield per unit of nutrient applied.[15] If, for example, the farming system is producing milk and/or meat, the PFP should consider the amount of fertilizer used vis-à-vis the amount of milk and/or meat produced. The application of the PFP factor may not be possible in all cases, such as for large farms producing a number of different products, without a defined fertilizer management

14 A detailed list of opportunities to reduce energy inputs in fertilizer is provided by FAO and USAID (2015).

15 An account of how to measure fertilizer use efficiency is provided by IFA, IWMI, IPNI and IPI (2015).

and accounting system. This measurement method does not include detailed assessments of cropping patterns and farm management practices.

Data sources: The indicator requires data on chemical fertilizer use; nutrient content of the bio-fertilizer co-produced and applied to the soil; the agricultural area; and crop yields before and after the intervention. At the farm level, data can be provided by the farmer or the organization providing the technology. In some cases, these data are registered for larger farms and are locally available.

Relevance to SDGs: This indicator is relevant for **Goal 12** "Ensure sustainable consumption and production patterns" (in particular **Target 12.4**) and **Goal 15** "Life on Land – Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss", in particular **Target 15.5** (Kinver, 2009).

INDICATOR: INDOOR AIR POLLUTION

Indicator description: Emissions of $PM_{2.5}$, PM_{10}, NO_X, SO_2, and other pollutants;

Measurement unit: milligrams/MJ;

Directionality: The impact is positive if the emissions decrease;

Relevance to sustainability: This indicator is primarily related to the air quality linked with human health. It is specifically relevant to emissions from solid fuel combustion and mitigation technologies that affect cooking and space heating habits. For example, surplus biogas can be used to fuel cookstoves and other heating appliances: it can reduce fuelwood consumption and related air polluting emissions. Traditional, low efficient biomass stoves that burn charcoal or fuelwood, produce a significant share of the pollutants affecting air quality by generating significant quantities of black carbon (FAO and USAID, 2015) which are reported as 2.5 and 10 micron diameter particles, i.e. $PM_{2.5}$ and PM_{10}.

In most poor rural households, women and children are responsible for cooking. However, all household members are at risk from the smoke resulting from cooking with traditional biomass, charcoal, or kerosene under poor ventilation. Resultant health complaints include cardiovascular, respiratory and eye diseases, as well as cancer. In 2012 alone, indoor air pollution was responsible for the premature death of 4.3 million people, and although women and children are more exposed, attributable mortality rates were slightly higher for men due to their larger underlying disease rates (WHO, 2014).[16]

When an energy intervention in an agrifood chain can also lead to the replacement of traditional biomass or fossil fuel-powered technologies with modern clean energy services at the household, all household members benefit from cleaner air and

16 In addition, when cooking with traditional biomass, women and children are at greater risk of receiving burns from open fires and poisoning from ingestion.

healthier and safer lives. Biogas or syngas-fuelled systems are examples of clean technologies that can reduce wood or coal burning.

Method and limitations: It is possible to measure air pollutant reduction induced by a clean energy technology in a household or in the locality. However, measurements have been complex, costly or time consuming in the past – but new methods are evolving (FAO and USAID, 2015).

Estimates of the mass of emissions of non-GHG air pollutants can be generated by measuring the mass of biomass (wood or rice husks) saved from combustion and using emissions factors for biomass burning (e.g. IPCC default factors for CO and NO_X).

In case of air pollution from cookstoves, a good proxy indicator would be the tier system adopted by the Global Alliance for Clean Cookstoves (GACC) as presented in the Clean Cooking Catalog (http://catalog.cleancookstoves.org/). Each cookstove is assigned a score from Tier 0 to Tier 4, on the basis of the ISO International Workshop Agreement (IWA) on Tiers of Performance (Table 3.3). The interim international guidelines for stove performance, including efficiency, total emissions, indoor emissions, and safety, aim to provide a common and easy-to-understand terminology to make decisions about technology options. If the introduction of a technology involves the adoption of a different cooking device (for example the availability of biogas enables a switch from a charcoal stove to a biogas stove), the IWA Tiers of Performance and the Clean Cooking Catalogue can provide an indication of the associated reduction of indoor air pollution.

TABLE 3.3. Performance of cookstoves and emissions in tiers, as defined by the ISO International Workshop Agreement.

Indoor emissions Sub-tiers		
	Indoor emissions CO (g/min)	Indoor emissions PM2.5 (mg/min)
Tier 0	>0,97	>40
Tier 1	≤0,97	≤40
Tier 2	≤0,62	≤17
Tier 3	≤0,49	≤8
Tier 4	≤0,42	≤2
Efficiency/fuel use Sub-tiers		
	High power terminal efficiency (%)	Low power specific consumption (MJ/min/L)
Tier 0	<15	<0.050
Tier 1	≥15	≥0.050
Tier 2	≥25	≥0.039
Tier 3	≥35	≥0.028
Tier 4	≥45	≥0.017

Source: adapted from Global Alliance for Clean Cookstoves, 2016.

Data sources: Indoor air pollution can be measured directly, or information can sometimes be obtained from the equipment provider. Measurement can be a long and time-consuming activity, so when the new technology involves the switch of a cooking device and fuel, the IWA Tiers of Performance and the Clean Cooking Catalogue can provide an easier proxy indication.

Relevance to SDGs: This indicator is relevant for **Goal 3** "Good Health and Well-being – Ensure healthy lives and promote well-being for all at all ages", in particular **Target 3.9.**

INDICATOR: WATER USE AND EFFICIENCY

Indicator description: Change in amount of water used (i) in absolute terms and (ii) per quantity of output;

Unit of measurement: (i) litres and (ii) l/kg;

Directionality: The impact is positive if the amount of water used in absolute terms and per quantity of output decreases;

Relevance to sustainability: In many developing areas, water is a scarce resource so its efficient use is a priority. This indicator is relevant for those clean energy technologies that use water and/or can have an impact on water use efficiency. These include biogas-based systems (which may need freshwater to dilute the feedstock), cold storage (which can decrease food losses and therefore indirectly reduce the water needed to produce the food) or irrigation (which can allow a more efficient irrigation practice that was impossible before the intervention). Supplying drinking water to animals can involve pumping and storage. Simply repairing leaks in the system can reduce water wastage.

In the milk value chain, water requirements vary considerably across countries according to local practices, level of mechanization and production system. For instance, in countries where mechanization is high, most water is needed for irrigation of crops and pasture for feed production (FAO and USAID, 2015). An energy intervention could improve irrigation water efficiency. However, due to reduced operation costs for pumping with PV systems compared to diesel engine-powered systems, a rebound effect might result in excessive and unsustainable water pumping (ESCWA, 2014). This would lower the underground water table or reduce surface water availability since farmers have no incentive to limit water pumping if energy is free and no quotas are imposed.

Biogas technologies based on manure may require water with an input/output ratio depending on local conditions. If additional water is required, it is important to identify whether the source of water is potable or not, and quantify the additional volume demanded. Moreover, the additional demand for water may result in increased competition for a scarce resource with other nearby domestic or industrial users.

Access to energy for cold storage can contribute significantly to reducing water footprints by lowering food wastage.

In intensive rice production, inefficiently applied nitrogen may lead to water pollution, decreasing soil productivity and GHG emissions (FAO and USAID, 2015). Digestate application could reduce these negative impacts, and energy interventions can help measure and match the actual water and fertilizer use to crop requirement. Moreover, water use can be minimized by keeping the soil moist by frequent applications through managed irrigation rather than flooding using high water volumes between longer periods (the former approach also minimizes anaerobic conditions, increases soil organism diversity and reduces methane emissions).

When additional water is required for processing of agricultural products (e.g. pre-heating, cleaning, humification, and evaporative cooling), the actual water volume required depends on the efficiency of the processes and the climate conditions.

A change in water use can also have an impact on the workloads of women and men, depending on the division of labour in the local context. This specific issue is considered under the "time-saving" indicator.

Method and limitations: In general, water use per unit of product should be monitored and measured to ensure that the resource is not overexploited or wasted, especially in water scarce areas. When possible, the water footprint of a product (water volume consumed per unit of product) should be considered, which is the sum of the water footprints of each of the process steps taken to produce the goods for the market (Mekonnen and Hoekstra, 2011). However, the water footprint approach is often complicated or impossible, and a simpler water end-use approach can be adopted.

Water use can be classified as blue, green or grey depending on the water source (Mekonnen and Hoekstra, 2011):

- the blue water footprint is the volume of surface and groundwater consumed or evaporated as a result of producing a good;
- the green water footprint is the rainwater consumed; and
- the grey water footprint is the volume of freshwater required to assimilate the load of pollutants based on existing water quality standards.

When possible, a distinction between these three components should be made explicit.

Data sources: Water use and quality can be measured in the field and/or reported by users or the technology provider.

A useful tool is the WEAP (Water Evaluation and Planning System)[17] software that takes an integrated approach to water resource planning. It incorporates supply, demand, water quality and ecological considerations into a practical tool for integrated water resource planning. This tool calculates water demand, supply, run-off, infiltration, crop requirements, flows and storage, pollution generation, treatment, discharge and in-stream water quality under varying hydrologic and policy scenarios. It also provides information on available water resources.

17 See more at: http://www.weap21.org/.

Relevance to SDGs: This indicator is relevant for **Goal 12** "Responsible Consumption and Production – Ensure sustainable consumption and production patterns", in particular **Target 12.2,** and **Goal 6** "Clean Water and Sanitation – Ensure availability and sustainable management of water and sanitation for all", in particular **Target 6.4.**

INDICATOR: WATER QUALITY

Indicator description: Change in pollutant loadings, measured as (i) annual nitrogen (N) and phosphorus (P) content, (ii) temperature change, and (iii) pH change of the watershed;

Unit of measurement: (i) mg/litre; (ii) ˚C; (iii) pH level;

Directionality: The impact is positive if the pollutant load (measure as mg/litre) decreases and/or the temperature and the pH of water do not change;

Relevance to sustainability: This indicator is closely connected with the indicator on fertilizer use and efficiency. If an energy technology impacts fertilizer or pesticide use (e.g. due to a new energy crop plantation) or generates by-products with nutrient value, its effects on land and water should be measured. Manure, N and P containing fertilizers, and pesticides can result in excess nutrients and pesticides flowing into waterways and bodies of water via surface run-off or infiltration to groundwater as well as through volatilization (FAO, 2011c). Nutrient pollution and pesticide contamination of water can have an impact on the environment but also on human health (drinking water).

Wastewater from food production and processing facilities could be high in N and P, contributing to biochemical oxygen demand (BOD) if discharged into waterways untreated. Discharge of high-BOD water is problematic because decomposition can consume all of the dissolved oxygen, suffocating aquatic animals (National Research Council, 2008).

Even energy interventions such as cold storage and other processing activities may impact water quality in some cases. In general, food or bioenergy processing facilities may discharge acidic or alkaline effluents that generate changes in water pH, negatively affecting aquatic life to a degree depending on the properties of the watershed (FAO, 2011c). Some types of effluent may be discharged at a high temperature, whereas others can be briny (due to salt content), or contain greases and oils.

Method and limitations: The maintenance of water quality in effluents from food processing activities should be measured and monitored, taking into consideration:

- the N and P loadings in the water due to the energy intervention as compared with the benchmark scenario; and

- the pollutant loading, discharge temperature, and pH levels.

The measurement method used depends on factors such as the availability of data and time, technical expertise, and the complexity of the scenario to be analysed. When data for the benchmark scenario are not available, values taken from the literature can be used to estimate the average loadings.

An important limitation to this indicator is that direct physical, biological and chemical measurements require skilled personnel and specific tools that can be expensive and time-consuming to operate. Moreover, water pollution is difficult to allocate precisely since N and P fertilizers and pesticides are applied throughout the agricultural production cycle. The extent to which they enter surface water depends on the methods and times of application, distances from recipient water bodies, and many other factors (FAO, 2011c). Therefore, data collection regarding N and P applications has a large degree of uncertainty, possibly leading to inaccuracies.

Data sources: Data on fertilizer and pesticide application, livestock production and other activities that result in N and P reaching groundwater (by infiltration) or surface water (by runoff), could be collected from project implementers, equipment providers or through field visits.

Total nitrates and phosphates, concentrations in waterways and lakes as well as pollutant concentrations (including BOD), pH and temperature of effluents and their discharge flow rates, may need to be measured. Physical, biological and chemical measurements as well as interviews and surveys in the field or processing plant site can aid this purpose. Information on these values can be enhanced and complemented by contextual information about the overall health of water bodies in the investment field or processing plant.

Relevance to SDGs: This indicator is relevant for **Goal 6** "Clean Water and Sanitation – Ensure availability and sustainable management of water and sanitation for all", in particular **Target 6.3.**

INDICATOR: FOOD LOSS

Indicator description: Amount of food loss avoided as a direct consequence of the energy intervention;

Unit of measurement: kg of food or agricultural products;

Directionality: The impact is positive if the indicator increases;

Relevance to sustainability: This indicator is relevant to all energy technologies that help prevent food spoilage from poor post-harvest storage, lack of cooling, heating, or cooking. This is particularly important in developing countries where 40 percent of food wastage occurs post-harvest and during processing (FAO, 2016a) – rather than in developed countries, where the losses are mainly at retail or consumption level. Losses may occur due to managerial and technical constraints in harvesting techniques, and/or in storage and cooling facilities (FAO, 2016a). Food loss at a certain stage of the value chain corresponds to inefficient use of natural resources needed (e.g. energy, water, soil, time) and related impacts (e.g. GHG emissions) to produce the product up to that stage. Moreover, a food loss can be, under certain circumstances, a "missed opportunity" to add value to the product during subsequent stages of the value chain. It is also a missed opportunity to improve food security. Indeed, full costs of food wastage[18] is estimated at US$2.6 trillion/year, which includes US$700 billion in environmental costs and US$900 billion in social costs (FAO, 2013). In the case of milk spoilage at production level, growing feed for dairy cows increases soil degradation; and if the milk is spoilt, there is no benefit from using the soil (FAO, 2014b). This loss can even have a social cost if farmers are fighting for fertile lands (FAO, 2014b).

Method and limitations: Food loss can be very difficult to quantify, as there usually are no control groups in which the losses do not occur. Calculation of food wastage avoided compares the initial situation prior to the energy intervention and the post-intervention situation. This indicator is linked to other indicators such as water use and efficiency, since a reduction in food wastage will have an impact on the total amount of resources used at other stages of the food chain (e.g. if milk wastage is avoided, it means that the amount of water to produce the feed for the animals is also not wasted).

For each food item, the share that is lost can be quantified or estimated during production or handling. This includes both avoidable and unavoidable food wastage due to insufficient crop protection, incomplete harvest, improper storage, improper processing, poor packaging, inappropriate carriers giving food damage during transport, and wasteful marketing practices. If possible, data should be disaggregated by gender so it is clear who is involved in food loss reduction and where along the value chain.

Materials that are put to another use, such as for animal feed or as a source of compost or bioenergy, can be subtracted from the "lost" quantities to determine actual waste.

Data sources: The required data concerning food wastage and loss can be collected at household/community level through surveys and/or provided by the technology provider. In addition, studies on food wastage can provide information even though they are usually undertaken at a macro-economic level by World Bank Data, FAOSTAT, national government, etc.

Relevance to SDGs: This indicator is relevant for **Goal 2** "End hunger, achieve food security and improved nutrition and promote sustainable agriculture", in particular **Target 2.1** and **2.2,** and **Goal 12** "Responsible Consumption and Production – Ensure sustainable consumption and production patterns", in particular **Target 12.3.**

18 **Food loss** refers to a decrease in mass (dry matter) or nutritional value (quality) of food that was originally intended for human consumption. These losses are mainly caused by inefficiencies in the food supply chains such as poor infrastructure and logistics, lack of technology, insufficient skills, knowledge and management capacity of supply chain actors, and lack of access to markets. In addition, natural disasters play a role.
Food waste refers to food appropriate for human consumption being discarded, whether or not after it is kept beyond its expiry date or left to spoil. Often this is because food has spoiled but it can be for other reasons such as oversupply due to markets or individual consumer shopping/eating habits.
Food wastage refers to any food lost by deterioration or waste Thus, the term "wastage" encompasses both food loss and food waste (FAO, 2013).

INDICATOR: LAND REQUIREMENT

Indicator description: Productive land converted as a direct consequence of the energy intervention;

Unit of measurement: Hectares;

Directionality: The impact is negative if the indicator increases;

Relevance to sustainability: Some energy interventions lead to land requirement and a change in the use of the land. A typical example is a bioenergy intervention, which makes use of ad-hoc grown energy crops, thereby using land previously occupied for other activities. Energy interventions could also occupy land due to the introduction or installation of new equipment. Sometimes (like in the case of a solar pump which occupies more land than the replaced diesel pump) the change in land use is negligible. Other times (such as for the installation of a large biogas plant) the change in land use is not negligible.

This indicator is typically relevant for (i) technologies that involve biomass production from crops, (ii) ground-mounted solar PV panels that require land, (iii) hydropower that involves land lost for damming, (iv) wind farms that occupy around five percent of the agricultural land area, and (v) geothermal plants that utilize area adjacent to the resource. The conversion of degraded or non-productive land area is not considered by this indicator.

Often, land use change is not a direct consequence of the energy intervention but rather an indirect effect; the indicator does not apply in these cases. For example, when introducting solar pumps to replace manual irrigation, this indicator would consider the change in the area occupied by the pumps – but not the change in crop patterns towards more value-added crops or the extension of cultivated area due to the introduction of solar irrigation.

The land requirement indicator is also linked to other social indicators such as income and employment, particularly in the case of medium- to large-scale projects. Land use change or land requirement may generate conflicts if the local conditions are not carefully analysed and local stakeholders are not properly engaged. Women often have a smaller voice and influence in decision-making than men at various administrative levels and in the private sector. With less scope to communicate their needs, they and other marginalized groups risk benefiting relatively less from land use change or not at all, or even being disadvantaged in some way.[19]

Method and limitations: This indicator measures the area of land occupied or converted to another use as a direct effect of the energy intervention. For example, the requirement of large parts of land by ground-mounted solar PV panels or ad-hoc cultivation for energy cropping can be considered a direct effect of the energy intervention. An energy intervention can also enable land use change, but these

19 If the impact on land requirement is important, it would be interesting to learn who was involved in the decisions concerning land use change and how the subsequent changes have had an impact upon different social groupings, including women.

indirect effects are not covered by the indicator, such as the possibility to expand irrigated land area due to the new electricity generation capacity.

While the land requirement (e.g. area occupied by a biogas plant) depends mainly on the size of the intervention, the amount of land converted (e.g. land converted to energy crop production to feed the biogas plant) depends on the local situation. In these cases, land monitoring should take place under a regular schedule, which sometimes may require remote geo-sensing techniques.

Data sources: The indicator can be measured from field survey missions, by interviews with stakeholders or through remote satellite geo-sensing.

Relevance to SDGs: This indicator is relevant for **Goal 15** "Life on Land – Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss", in particular **Target 15.5.**

INDICATOR: GHG EMISSION

Indicator description: Change in (i) the absolute amount of GHGs emitted and (ii) the emissions per unit of product as a result of the intervention;

Unit of measurement: (i) kg of CO_2eq and (ii) kg of CO_2eq/kg of product;

Directionality: The impact is positive if emissions in absolute (kg of CO_2eq) and relative terms (kg of CO_2eq/kg of product) decrease;

Relevance to sustainability: Many energy interventions reduce CO_2 emissions compared to the fossil fuels they displace. For instance, cold store technologies powered by non-renewable electricity can be a source of emissions. Avoidance of other GHG emissions such as enteric methane from ruminants or nitrous oxides from fertilizer use (FAO, 2013) should be assessed, although mitigation is difficult to achieve. Other interventions can indirectly affect GHG emissions, for example by impacting the use of fossil fuels for fertilizer manufacturing.

In cases where traditional use of biomass for energy (e.g. combustion of fuelwood on open fires for cooking or heating) is to be compared with the use of modern bioenergy (such as improved cook stoves or electricity), the GHG emissions should be measured based on the amount of fuel saved and the emission factors of the source.

Method and limitations: Any change in GHG emissions of a value chain refers to the total amount of GHGs emitted during the agricultural phase. This includes GHG emissions from on-farm energy and land use, non-energy-related emissions such as CH_4 and N_2O, and emissions from food transport and processing, before and after the energy intervention.

A number of tools are readily available to assess GHG emissions from agriculture.[20] Other tools exist to assess GHG emissions due to energy use in food processing (some of them are presented in FAO and USAID, 2015). Preference should be given to using tools that are compliant with IPCC 2006 Guidelines for National GHG Inventories.[21]

Detailed data requirements depend upon the choice of methodology (FAO, 2011c), but in general will include information about:

- GHGs covered (e.g. CH4 for biogas and rice cultivation, CO_2 for technologies substituting fossil fuels);
- source of emissions;
- land use change (direct and/or indirect);
- transport of the commodity to the market (calculation method, transport means);
- energy required for on-farm production (e.g. irrigation, crop management) and processing of the commodity (cold storage, drying, etc.);
- source of energy for production and processing;
- by-products and co-products produced (e.g. slurry, heat); and
- comparison with displaced fossil fuels.

A detailed analysis of the GHG emissions associated with an energy intervention requires the assessment of avoided food loss. This is particularly relevant for energy interventions that improve food storage.

Data sources: This indicator can be based on the collation/computation of data or physical measurements (e.g. through surveys with practitioners or equipment providers). In some cases, data on emissions can be gathered through national/international statistical accounts or local studies, especially to estimate the change in GHG emissions at other stages of the value chain. The tools and IPCC Guidelines mentioned above also provide default values for emissions.

Relevance to SDGs: This indicator is relevant for **Goal 13** "Climate Action – Take urgent action to combat climate change and its impacts", in particular **Target 13.2.**

3.3.2. SOCIO-ECONOMIC IMPACTS

Energy interventions in the agrifood value chains can also affect access to energy, income, time available for other activities, and employment – hence on rural

20 A collation of these tools is available at http://www.fao.org/tc/exact/review-of-ghg-tools-in-agriculture/en/.

21 Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/.

development overall. Moreover, energy interventions can reduce health hazards associated with collection, transportation and use of fuelwood, charcoal and kerosene, such as bruising, headache, neck ache, back ache, knee problems, poisoning, encounters with wild animals and snakes, as well as rape and attacks. Although it is difficult if not impossible to measure the specific impacts induced by a single energy intervention, the indicators on "indoor air pollution" (presented above) and "access to energy" (presented below) are useful proxy indicators for health impacts.

This section introduces some indicators that can help measure socio-economic impacts.

INDICATOR: ACCESS TO ENERGY

Indicator description: Change in access to energy;

Unit of measurement: Index of access;

Directionality: The impact is positive if the indicator increases;

Relevance to sustainability: Energy infrastructures do not always exist and when they do, they may not be reliable. Therefore, especially in rural and isolated areas, energy technologies can enable more productive and safe agrifood chains, or displace the use of fossil fuels (e.g. diesel, kerosene). Improved access to modern and efficient renewable energy allows agrifood markets to be decoupled from the volatile fossil fuel markets.

Over one billion people still lack access to electricity. Energy interventions in the agrifood chain can allow new types of productive activities or businesses to grow within the food sector, but can also provide excess energy for other uses such as lighting and new services like the use of mobile phones and internet. These additional uses can have a direct impact and positive spillover effect on education, income generation and several social aspects. Furthermore, surplus energy can contribute to a transition towards cleaner fuels for cooking and heating. This indicator is linked to indoor air pollution and ultimately to human health.

The lack of access to electricity particularly affects women and thus perpetuates gender inequality. Coupled with their primary responsibility for domestic chores, a large proportion of their day is lost on unpaid, labour-intensive and repetitive tasks. Women's lack of access to electricity and their limited mobility also restricts them to labour-intensive, low productivity subsistence activities on the farm, primarily at the production stage.

All energy technologies which allow surplus modern energy generation are relevant to this indicator (e.g. a PV-based intervention which provides surplus electricity to be used for other activities, or a biogas-based intervention which allows surplus biogas to be used for cooking).

Method and limitations: At the household level, introduction of an energy technology can have an impact on access to electricity or cooking fuels. For the measurement of this indicator, it is suggested to follow the multi-tier framework for household energy access developed by the World Bank in collaboration with other partners for Sustainable Energy for All (Table 3.4 and Table 3.5). This method recommends the assessment of energy supply attributes against a number of criteria, which differ for electricity services and cooking solutions, and assigns a score to each tier or level from 0 to 5 (Table 3.4 and Table 3.5). The levels (with specific weights) are then combined in an access index.[22]

Alternatively, this indicator can be expressed or complemented by more qualitative considerations, such as the type of energy source and energy service obtained as a consequence of the energy intervention. Qualitative information could also help capture the abovementioned reasons that make access to technology harder for women than men.

This indicator is measured at the point of technology adoption and hence has no impact at different stages along the food value chain.

TABLE 3.4. Tier system classification for access to electricity services.

	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Tier criteria	Not applicable	Task lighting Phone charging	General lighting Television Fan (if needed)	Tier 2 and Any medium-power applicances	Tier 3 and Any high-power applicances	Tier 4 and Any very high-power applicances

Source: ESMAP, 2015.

TABLE 3.5. Tier system classification for access to cooking solutions.

<table>
<tr><th></th><th></th><th></th><th>LEVEL 0</th><th>LEVEL 1</th><th>LEVEL 2</th><th>LEVEL 3</th><th>LEVEL 4</th><th>LEVEL 5</th></tr>
<tr><td rowspan="3">ATTRIBUTES</td><td rowspan="2">1. Indoor Air Quality</td><td>PM2.5 ($\mu g/m^3$)</td><td rowspan="2"></td><td rowspan="2">[To be specified by a competent agency such as WHO based on health risks]</td><td rowspan="2">[To be specified by a competent agency such as WHO based on health risks]</td><td rowspan="2">[To be specified by a competent agency such as WHO based on health risks]</td><td>< 35 (WHO, IT-1)</td><td>< 10 (WHO guideline)</td></tr>
<tr><td>CO (mg/m^3)</td><td><7 (WHO guideline)</td><td><7 (WHO guideline)</td></tr>
<tr><td colspan="2">2. Cookstove Efficiency (Not to be applied if cooking solutions is also used for space heating)</td><td></td><td>Primary solution meets TIER 1 efficiency requirements [to be specified by a competent agency consistent with local cooking conditions]</td><td>Primary solution meets TIER 2 efficiency requirements [to be specified by a competent agency consistent with local cooking conditions]</td><td>Primary solution meets TIER 3 efficiency requirements [to be specified by a competent agency consistent with local cooking conditions]</td><td colspan="2">Primary solution meets TIER 4 efficiency requirements [to be specified by a competent agency consistent with local cooking conditions]</td></tr>
</table>

22 For more information see https://www.esmap.org/node/55526.

			LEVEL 0	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
ATTRIBUTES	3. Convenience	Stove preparation time (min/meal)			<7	<3	<1.5	<0.5
		Fuel aquisition and preparation time (hrs/wk)			<15	<10	<5	<2
	4. Safety of Primary	IWA safety tiers			Primary solution meets (provisional) ISO Tier 2	Primary solution meets (provisional) ISO Tier 3	Primary solution meets (provisional) ISO Tier 4	
		OR Past accidents (Burns and unintended fires)					No accidents over the past year thatrequired professional medical attention	
	5. Affordability						Levelized cost of cooking solution (including cookstove and fuel) <5% of household income	
	6. Quality of Primary Fuel: Variations in heat rate due the fuel quality that affects ease of cooking						No major effect	
	7. Availability of Primary Fuel						Primary fuel is readily available at least 80% of the year	Primary fuel is readily available throughout the year

Note: CO = carbon monooxide; ISO = International Organization for Standardization; IWA = International Workshop Agency on Cookstove; PM = particulate matter.

Source: ESMAP, 2015.

Data sources: The required data can be collected at household and community levels through surveys, and/or can be provided by the technology providers.

Relevance to SDGs: This indicator is relevant for **Goal 7** "Affordable and Clean Energy – Ensure access to affordable, reliable, sustainable and clean energy for all", in particular **Target 7.1.**

INDICATOR: HOUSEHOLD INCOME

Indicator description: Change in monetary in-flows, such as wage and revenues, and out-flows;

Measurement unit: US$ or local currency, disaggregated by gender if possible;

Directionality: The impact is positive if the change in net flows is positive;

Relevance to sustainability: Energy interventions can contribute directly to income generation through a change in wages (for employed agents) or an increase in net incomes from the sale, barter, and/or own consumption of products (for self-employed agents).

Energy interventions that reduce food waste, increase crop yields and/or improve the quality of the product can indirectly increase household income. Energy interventions can extend the lifetime of a product and/or lead to better quality, thus generating increasing sales and/or allowing greater access to (higher priced) formal or international markets.

Energy technologies could result in lower household energy bills due to the displacement of costlier alternatives. Especially in remote areas where a significant amount of fuel is spent on transporting agricultural commodities, cold storage applications can optimize transport efficiency by reducing waste or reduce the time spent on transporting the product to the market. As a result, transport to the market can happen less often and can be better targeted. Less waste and spoilage can thus increase revenues from sales and reduce the time spent in transporting the product, which can then be spent on other income-generating activities.

Increased household income does not necessarily translate into women's economic empowerment. The extent to which gender equality is promoted depends on who earns the income (or saves on expenditures) and who then controls it. If men generate a higher income, it is highly likely that they will control it. If women see an increase in their income, for example by selling chilled evening milk the next morning or refrigerated vegetables that would have otherwise perished, they may or may not control how the money is then spent or saved. This will depend on household dynamics as well as other local cultural and socio-economic factors. It is a serious issue for many rural women who are often de-motivated when they do not share the benefits of their endeavours (IFAD, 2012).

When women do have control over their income, they are known to spend a higher proportion on improving the well-being of the whole household, including investment in children's education, health and nutrition – which all support economic growth in the long-term. Rising incomes also help to improve women's self-esteem and bargaining power at home and in the community, which are important steps towards gender equality. Relationships between husband and wife are also often reported to improve as a result of women's improved economic status (Revenga and Shetty, 2012).

Method and limitations: Income can be measured by looking at:

- Change in **wages:** for employed people, information on hourly wages is easily collected. For self-employed people, the change in income can be measured by introducing a cost opportunity for the time spent on farming activities. If the local wage is not known, the minimum wage for rural agricultural services in the country or region can serve as a proxy.

- Increase in **revenue** from sales due to higher quality or quantity sold: the energy intervention can create higher mark-up[23] opportunities, higher quantities produced with the same inputs or a reduction in food waste/spoilage.

- **Savings** on energy spending and other agricultural inputs: purchasing fossil fuels and chemical fertilizers often constitute a large share of household expenditures, which can be significantly reduced by alternative renewable energy sources or use of co-products or residues.

- **Diversification** of the sources of income: in some cases, energy interventions can also have an impact outside of the targeted value chain, or can help diversify economic activities. For instance, a biogas milk chiller can increase revenues from milking activities but also produces bio-slurry, which in turn may increase agricultural yields.

While information on formal wages is easy to collect, measurements of the income of self-employed households and individuals are not straightforward. They require information on how much time the farmer spends on each activity and assumptions about opportunity costs (what the farmer would do instead). If possible, income assessment should include an accurate understanding of the local context and dynamics. In particular, factors such as household size, distribution of income among household members, gender, ages and consumption needs of household members should be taken into consideration. In order to understand whether increases in household income promote gender equality, measurements would ideally be disaggregated by sex and differentiate between who earns it and who controls what proportion.

Revenues can be measured by collecting information on formal and informal prices, quantity sold and waste/spoilage. They strongly depend on market access.

Savings on energy spending depend on availability and prices of alternative energy sources.

Data sources: The required data can be collected at household or community levels through surveys. As well, studies on income in rural areas can provide information for the benchmark scenario, even though they might be performed at a macroeconomic level (e.g. World Bank Data, FAOSTAT, national data, etc.). Data about income after the energy intervention must be compared with the situation before the technology was adopted. Income throughout the various stages of the value chain could also be compared with national legally established minimum wages (if they exist) or with the minimum wage levels according to ILO standards – if no better data are available.

Relevance to SDGs: This indicator is relevant for **Goal 2** "End hunger, achieve food security and improved nutrition and promote sustainable agriculture", in particular **Target 2.3;** and **Goal 8** "Decent Work and Economic Growth – Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all", in particular **Target 8.2.**

23 Difference between selling price and cost per unit of production.

INDICATOR: TIME SAVING

Indicator description: Change in time spent in performing unpaid agricultural and/or household activities;

Measurement unit: Hours per week or per year, disaggregated by gender if possible;

Directionality: The impact is positive if the time spent decreases;

Relevance to sustainability: Energy interventions can directly reduce the time spent at each stage of the agrifood value chain. For instance, in the production stage, introducing solar water pumps can reduce the time spent carrying water. In the post-harvest and storage stages, mechanical drying is faster than drying products on shelves or in the open air. In the processing stage, activities such as mechanical grinding, dehusking or pressing is more time-efficient than performing those activities manually. Often these particular tasks are performed by women. Energy technologies can therefore reduce farm labour and free people, especially women, from labour-intensive, low productivity, subsistence activities in the value chain and give them the choice to spend their time on more productive, higher-paid activities as well as on recreational and learning activities.

Energy interventions that reduce the use of fuelwood and charcoal or the need to collect water can improve well-being, especially of women. Modern energy services can improve sustainable development at the community and local levels by reducing hazards and health risks. On the other hand, technologies that require additional water (such as a small biogas system) or residues that are normally used as biomass for heating (mostly for cooking and drying produce) can have a negative impact on the time spent collecting these resources, and therefore impose additional barriers on whoever is in charge of the collection activities – which often are women.

Time is also required to travel to the nearest market to buy the agricultural inputs (seeds, equipment, fuel, and fertilizer) or to sell the products. This can limit productive potential of women when they lack transport or safe passage to the markets, or when they are restricted in movement beyond the home owing to cultural norms. As discussed above in the *household income* indicator, cold storage applications allow better preservation of food quality and can reduce the time spent transporting fresh produce to market, or at least increase transport efficiency by reducing waste.

Method and limitations: A straightforward measure of this indicator is to assess how much time is saved by men, women and children as a consequence of introducing the energy technology. An understanding of the division of labour and time use by men and women is crucial for evaluating time savings connected to energy interventions. Therefore, their main daily activities should be documented together with their income-generating activities, as well as their caregiving and household management work. This is crucial to ensure that no single group of participants is over-burdened or worse-off after the energy intervention.

Mapping and analysing the supply and demand of wood resources and watersheds could help quantify the time involved.

Similarly, the average time spent by men and/or women to reach the market should be taken into account, and the person who is in charge of buying the inputs and/or selling the final produce should be clearly identified.

Data sources: The required data on time spent on different activities should be collected at household/community level through detailed analysis. Direct observation, where trained researchers observe individuals and record their activities, is one of the most common and preferred approaches, but it requires skilled observers and may be costly. If this direct approach is not viable, the "interviewer administered time diary" is an alternative. In this method, the respondent describes each activity throughout the day in his/her own words (FAO, 2011c).

The time use survey should focus on the households' single components (men, women, children, girls, boys, and elderly people). Additional information about the use of the time saved for different activities (e.g. education, economic/trading, and leisure) would be beneficial.

Relevance to SDGs: This indicator is relevant for **Goal 2** "End hunger, achieve food security and improved nutrition, and promote sustainable agriculture", in particular **Target 2.3; Goal 5** "Gender Equality – Achieve gender equality and empower all women and girls", in particular **Target 5.8;** and **Goal 8** "Decent Work and Economic Growth – Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all", in particular **Target 8.5.**

INDICATOR: EMPLOYMENT

Indicator description: Net jobs created along the agrifood value chain, and shares of:

- skilled or unskilled jobs, disaggregated by gender if possible; and
- temporary part-time or indefinite full-time jobs, disaggregated by gender if possible;

Unit of measurement: Number of net job created, hours worked per year and hourly wage, disaggregated by gender if possible;

Directionality: The impact is positive if net jobs increase;

Relevance to sustainability: The introduction of energy technologies can create jobs due to the operation of the technology or the development of a business around the new technology. However, jobs in agriculture are expected to decrease as mechanization increases, therefore certain energy interventions may have a negative impact on employment. For this reason, the indicator measures net job creation along the value chain. Job creation at one stage of the value chain may be offset by job losses in other stages as a direct consequence of the introduction of the technology.

After assessing the net number of jobs created by the introduction of a technology, an important aspect to assess is the possibility of maintaining the job. Jobs can be temporary (e.g. seasonal) or indefinite (the duration involves continuous service intended to last for an indefinite period of time). This is an important aspect to be taken into account.

The jobs created may be skilled or unskilled. Skilled labour requires training and/or education and is normally better remunerated and more productive. Consequently, an energy intervention that requires people with fewer qualifications possibly has more potential to distribute income opportunities, reduce poverty, promote rural development and improve the socio-economic situation in a rural area.

The trends in the gender and age balance of the workforce are of interest for socio-economic development, since certain operations in the value chains may typically be undertaken by certain demographics of the local population. Moreover, it is important to identify who (women/men) obtains what type of work (skilled, unskilled, temporary, indefinite, part-time, and full-time) in order to understand if employment changes have a positive or negative effect on gender equality.

Method and limitations: This indicator is measured by the net number of jobs created as a result of an energy intervention. Conventionally, self-employed farmers and family workers are included in the count of workers. For the sake of statistics, the number of jobs is often quoted as full-time equivalents (FTEs), defined as a job that occupies an employee for 30 or more hours per week (FAO, 2011c).

- The measurement of direct jobs created by the energy intervention requires consideration of (i) the different steps of the value chain: feedstock production and harvesting; product processing; transport; and (ii) the phases of technology deployment: production/manufacturing of the technology (plants and equipment); installation, operation and maintenance of the technology (plants and other equipment).

This indicator also provides information about job losses that could occur as a result of the energy intervention at each step of the value chain. Many energy technologies are relatively labour-intensive in their installation, while the mechanization of some agrifood production or processing activities may reduce employment.

When the manufacturing of the technology is performed abroad it must be decided whether or not these jobs should be included in the analysis. This indicator does not attempt to measure indirect or induced job creation or spillover effects, but focuses on the targeted value chain.

For the jobs created within that value chain, the indicator should also consider information about their durability and the potential qualifications of the workforce. The former can be assessed by the contract duration (fixed-term versus indefinite) or, in the case of informal labour, by the kind of activities performed.

Due to particular social conditions, some employed people could remain poor even if they have a full-time job (United Nations, 2001). However, the indicator does not assess the quality of the jobs created in terms of security and decency, or the quality of labour conditions, which are beyond the scope of this analysis.

Data sources: Data required are the number of jobs created or lost as a result of the energy intervention along the value chain, the job duration and the percentage of skilled workers, all disaggregated by gender. Such data can be collected at household or community level, and it can be gathered from processors through surveys or (ex-ante) from the technology providers.

Useful information on jobs created by renewable energy technology, globally and by selected country/region, can be found in the IRENA report "Renewable Energy and Jobs – Annual Review 2016".

Relevance to SDGs: This indicator is relevant for **Goal 8** "Decent Work and Economic Growth – Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all", in particular **Target 8.5,** and **Goal 5** "Gender Equality – Achieve gender equality and empower all women and girls", in particular **Target 5.8.**

3.4. SENSITIVITY ANALYSIS

Milk spoils fast if not chilled after milking. As accesss to markets in rural areas is often hampered by poor infrastructure, cooling allows for milk storage and prevention of food losses.
Source: © Jörg Boethling/visualindia

Once the flows of costs and benefits as well asd related indicators are analysed and calculated, the robustness of these indicators to changes in one or more inputs and/or outputs can be tested using a sensitivity analysis. Simple methods are available for modelling risk, requiring minimum expertise in statistics and probabilities through user-friendly computer programmes.

A relevant element of risk is the price of the agricultural commodity produced, which is a key element to calculating the investment benefits. If the energy technology/practice increases production and is adopted by many value chain agents in a context where access to markets is limited (for instance because of bad roads and infrastructure), there is a supply excess on the local market. The increase in quantity produced in excess of demand causes its price to fall, thereby significantly reducing the profits of the producer. This is more likely to happen for commodities like milk with a very short lifetime, and in remote areas far from large towns and markets, such as in many African village contexts. Access to markets must therefore be analysed during the feasibility analysis and a sensitivity analysis, considering a negative variation of the produce's market price, should be performed.

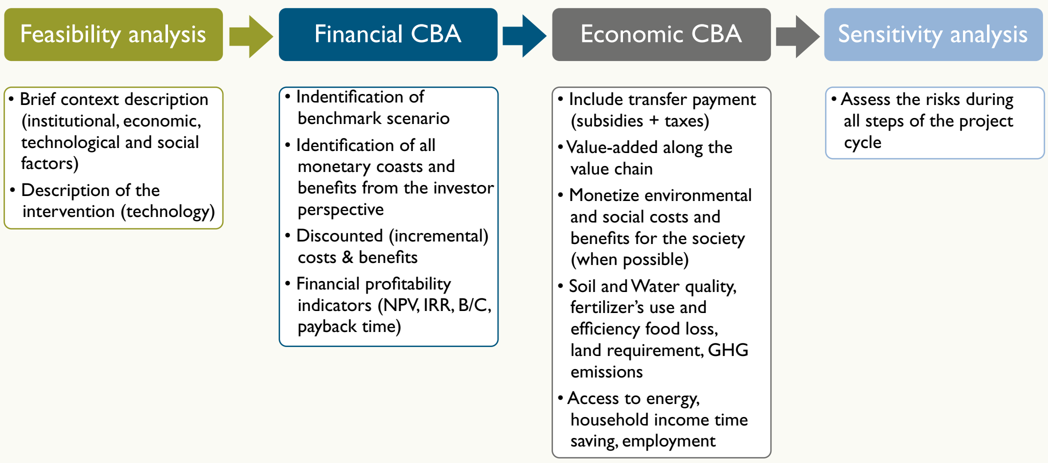
In practical terms, quantitative risk analysis complements classical FEA by providing a more detailed understanding of the investment dynamics and uncertainties. The insights gained by quantitative risk analysis may be useful for project design and evaluation. Detailed quantitative risk and sensitivity analyses are beyond the scope of this study, but they can be used to identify and evaluate the main risks factors.

When applying sensitivity analysis techniques to energy interventions, important variables are for instance local energy prices, local subsidies and local taxes.

Figure 3.5 illustrates the methodology described in this section and gives an overview of tools and impacts to consider at each stage. This methodology is applied to selected energy interventions/technologies for the milk, vegetables or rice value chains.

FIGURE 3.5. Description of a standard methodology for a sound and comprehensive cost analysis of energy interventions in the agrifood value chain.

Source: Authors.



4. COSTS AND BENEFITS OF THE SELECTED VALUE CHAIN TECHNOLOGIES

In this section, the methodology illustrated in Section 3 is applied to selected clean energy technologies that can be used in the milk, vegetable and rice value chains. These technologies are (i) biogas for power generation, (ii) biogas-powered milk chillers, (iii) solar-powered milk cooling centres (for the milk value chain), (iv) solar cold storage, (v) solar irrigation (for the vegetable value chain), (vi) rice husk gasification, and (vii) solar rice processing (for the rice value chain). This section illustrates how the methodology can be tailored to the three value chains and technologies under analysis.

Each technology is described with regard to its technical aspects, associated costs and potential impacts from its deployment at farm or food processing level. Later in this section, the methodology is applied to real world examples for all technologies except for solar cold storage.

4.1. MILK VALUE CHAIN

Source: © GIZ/Angelika Jakob

4.1.1. BIOGAS FOR POWER GENERATION FROM DAIRY CATTLE

Biogas produced from cattle manure can be directly combusted for heating, cooking, generating electricity and producing methane.
Source: © GIZ/Dirk Ostermeier

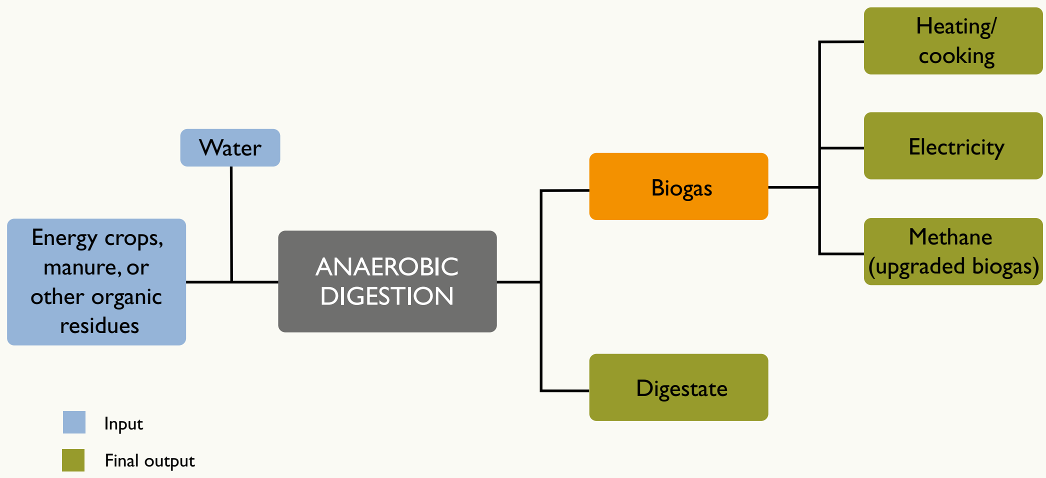
Biogas is produced through anaerobic digestion (AD), a biochemical process that involves the decomposition of organic matter by various species of symbiotic bacteria living in an anaerobic environment. It follows a four-step process: hydrolysis, acidogenesis, acetogenesis and methanogenesis. The biogas resulting from this process is primarily composed of methane (50–65 percent), CO_2 (30–45 percent), a small amount of water vapour (1–5 percent), and other gases usually present in small quantities (N2, O_2, H_2, NH_3, CO, H_2S). Biogas composition varies significantly with the organic feedstock. The typical biogas yield from cattle manure with 25 percent of dry matter (DM), of which 80 percent is organic, is 0.30 m^3/kg of organic dry solids, equivalent to a gas production of 60 m^3/tonne of feedstock.[24]

The resulting biogas can be directly combusted for heating, cooking, producing electricity and producing methane. As a result, it can drive many activities including cooking; heating buildings; heating water for cleaning, pasteurization or food processing; or powering a vehicle engine (similar to the role of compressed natural gas) (Figure 4.1). After upgrading the biogas by scrubbing it, the methane share can reach 97–98 percent, and it can be used as a substitute for natural gas or be injected into a natural gas pipeline. In all commercial biogas installations, some waste heat can be used to keep the digester at an optimum constant temperature of 38–41 °C, ideal for mesophilic bacteria.

24 Data can vary due to several factors. More information is available in SEAI (undated).

FIGURE 4.1. Overview of feedstock for biogas production and uses of biogas.

Source: Authors.



Water vapour and hydrogen sulphide must be removed before the biogas can be used in turbines and engines because hydrogen sulphide is a very corrosive gas: together with water vapour, it forms sulphuric acid, which may corrode metal surfaces. If the biogas is to be used for combined heat and power (CHP), the biogas pressure is usually increased with the aid of a gas compressor. The biogas is combusted in the gas turbine or in an internal combustion engine and the resulting energy is converted to electricity.[25] Surplus thermal energy can be used for heating purposes on-farm or exported to other processing facilities.

From 1 tonne of dairy cattle manure, with 25 percent DM, the 60 m^3 of biogas produced can generate around 125 kWh of electricity; whereas 1 tonne of liquid effluent (slurry) with 8 percent DM produces around 20 m^3 biogas, which can generate around 40 kWh.[26] The biogas potential of commercial dairy farms depends mainly on the amount of feedstock available, which is a function of the number of heads and their consumption of feed and its composition. In general terms, if one cow produces 40 kg of manure (8 percent DM), around 1 m3 of biogas is produced, which transforms into 1.44 kWh of electricity using CHP. As an example, a dairy farm with 400 dairy cows could produce enough biogas to produce between 400 to 500 kWh using CHP. The electricity produced will exceed by far the farm needs for cooling and milking (350,000 kWh produced from biogas per year, around 12,000 kWh used per year for cooling and milking).

To decrease the cost per kWh of the biogas installation, dairy farms should evaluate the possibility of using other on-farm or off-farm residues in co-digestion with cow effluents to increase electricity production. Common agricultural residues include grass silage, coffee residues, chicken manure, cut flowers residues, sisal residues, pig

25 It could also be used to generate electricity through a fuel cell. However, this process requires a very clean gas and is therefore not used in practice.

26 Assuming 60 percent methane content and a conversion efficiency of the ICE/genset of 35 percent (SEAI, undated).

manure and vegetable residues. Other common agro-industrial residues are instant tea residues, sugar mill residues, pineapple processing residues, distillery residues and meat-processing residues (GTZ, 2010).

Costs of plant and operation vary depending on the feedstock, its consistency and availability, as well as DM and methane content of the biogas produced.

The two conventional operational temperature levels for anaerobic digesters are:

- mesophilic digestion takes place optimally between 37 to 41 °C, or between ambient temperatures of 20 and 45 °C; and
- thermophilic digestion takes place optimally between 50 to 52 °C, or at elevated temperatures up to 70 °C.

The choice from the range of anaerobic digester designs depends on the feedstock, scale and scope of the activity. Table 4.1 illustrated various designs depending on the scale of the plant.

TABLE 4.1. Choice of anaerobic digester designs according to scale of plant.

Large and medium-scale applications	Small-scale applications
• covered anaerobic lagoon • plug-flow digester • up-flow anaerobic sludge blanket (UASB) • complete mix digester	• fixed dome digester • floating drum digester • bag digester

Source: Authors.

As a by-product of the anaerobic digestion process, the digestate can be used as a soil conditioner and fertilizer. The digestate consists of indigestible material and dead micro-organisms. The volume produced by a manure-fed biogas plant is usually around 90–95 percent of the digester total feedstock with 5–10 percent transformed into biogas. The digestate can be added directly to soils substituting a part of synthetic fertilizers. This adds indirect benefits such as fossil fuel savings from reduced volumes of fertilizer manufacture. The macro-elements (nitrogen, phosphorous and potassium) present in the feedstock will remain in the digestate. Although the concentration of elements in the digestate is fairly low, the nutrients are more readily available for plants, with macro-element concentrations ranging from 2.3–4.2 kg N, 0.2–1.5 kg P, and 1.3–5.2 kg K/tonne of digestate.

Performance of biogas systems depends on a number of factors caused by the sensitive nature of the biochemical process. For a performance assessment, the following elements need to be considered:

- ambient climate or process temperature (if heat is provided to the digester);
- availability of feedstock (wastewater; manure; slurry; other agricultural by-products such as deteriorated forage or crop residues; and food processing residues such as

from meat processing, vegetable peelings, and tomato skins) including seasonality of supply; and

- daily volume of feedstock, as well as its physical and chemical characteristics (texture and size; DM content; C/N and C/P ratios; pH; and temperature).

While cattle manure yields less biogas than other feedstocks, it has a lower retention time with a high presence of methanogenic bacteria since the digestion process has already begun in the rumen. In general, cattle manure will have a positive effect on anaerobic digestion because it brings micro-elements for feeding the existing bacteria, and new bacteria for replacing the dead ones. It also serves as a pH stabilizer, maintaining best digestion conditions inside the digester.

Based on the above, the optimal technology that best suits the characteristics of the feedstock can be chosen. While the bio-chemical process is basically the same behind all biogas technologies, for pro-poor and commercial applications within the milk chain, two technologies are more common:

- complete mix digester designs for small and medium dairy farms; and

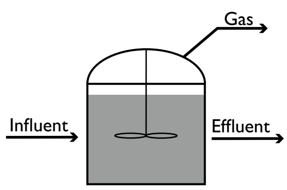
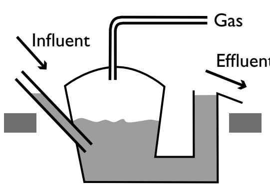
- fixed dome digesters for the domestic scale (Table 4.2).

These two designs can handle a wide range of dry matter contents in the feedstock.

Commercial applications require higher capital investment and give more efficient, larger-scale technology, but come with higher expectations for financial returns.

For **pro-poor applications,** the assumption is the presence of less than 10 head of cattle per plant, but with the possibility of mixing the manure with other feedstocks from the household, such as communal organic waste, wastewater slurry, or human sewage. The lowest possible capital and operational cost are sought, but the plant may be labour intensive and profitability is not the primary goal.

TABLE 4.2. Commonly used type of digesters in the dairy chain.

Type of digester	Advantages	Disadvantages	Schematic view
Complete mix digester with floating drum (for commercial dairy farms)	High biogas yield; handles dry matter (DM) content of 3–15%; retention time of 15–75 days	High capital and maintenance cost; high technology with moving parts; ideally a controlled mesophilic environment between 38–41 °C	
Fixed dome digester with no moving parts (for pro-poor dairy farms)	Steady temperature underground; low capital but moderate skill demand for construction and operation; no moving or rusting parts	Low biogas yield (difficult stirring, psychrophilic environment around 10–30 °C, usually non-optimized feedstock mix)	

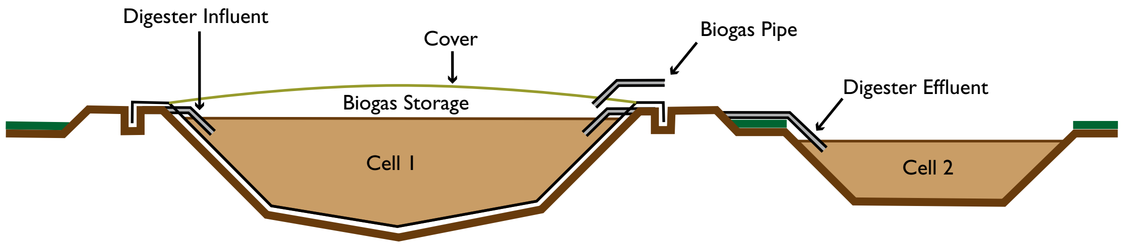
Source: FAO, 1992a.

A complete mix biogas technology is generally composed of a feeding system, a digester and a biogas upgrading system. From the digester, the biogas will flow into a storage tank.[27] In these systems, the dosing of feedstocks (solid and liquid) into the digester is automatized. The dosing devices can be controlled so that they automatically feed in small quantities several times an hour. In this way, the operator will be able to balance the feedstock variability to a certain extent.

BOX 6. COMMON DIGESTER CONFIGURATIONS FOR COMMERCIAL (E.G. ELECTRICITY GENERATION) AND NON-COMMERCIAL APPLICATIONS.

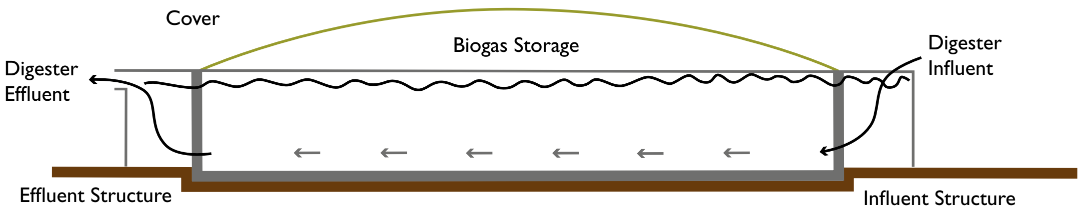
The most appropriate technology for a given situation is determined by the feedstock and its availability. For instance, when a large amount of cattle slurry is available, anaerobic lagoons or bag digesters may be preferred. The following are the most common digester configurations:

Covered anaerobic lagoon: An artificial pond where the liquid components are digested is covered by a pontoon or a floating cover. The digester consists of a feedstock intake, a covered area for biogas storage, a biogas extraction pipe, and an effluent take-off. An important consideration is the amount of solids the digester can handle. This design is the most economic option for large scale operations that contain 0 to 3 percent DM. The covered storage area for the biogas is protected from atmospheric exposure by sealed plates that extend down the sides of the pontoon into the liquid. Covered anaerobic lagoons are most effective in warm regions where ambient heat maintains the optimum digester temperature and no external energy has to be added to stabilize the temperature.

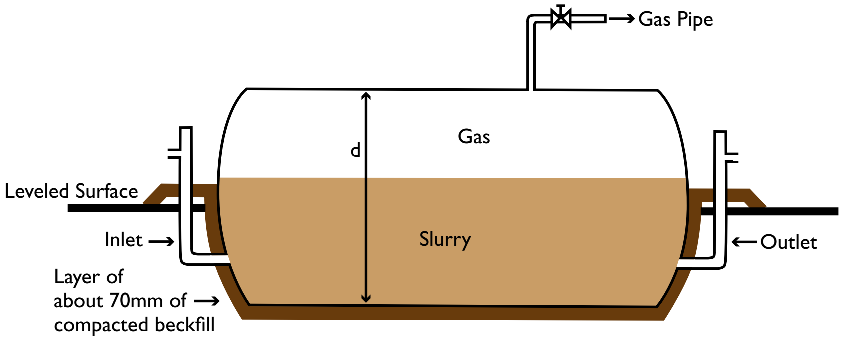


Plug-flow digester: A variation of a covered lagoon in which the organic feedstock is pumped horizontally and pushes the digested material out through the opposite end of the digester tank. The biogas is collected at the top of the tank. For this technology, there is usually no need to add heat.

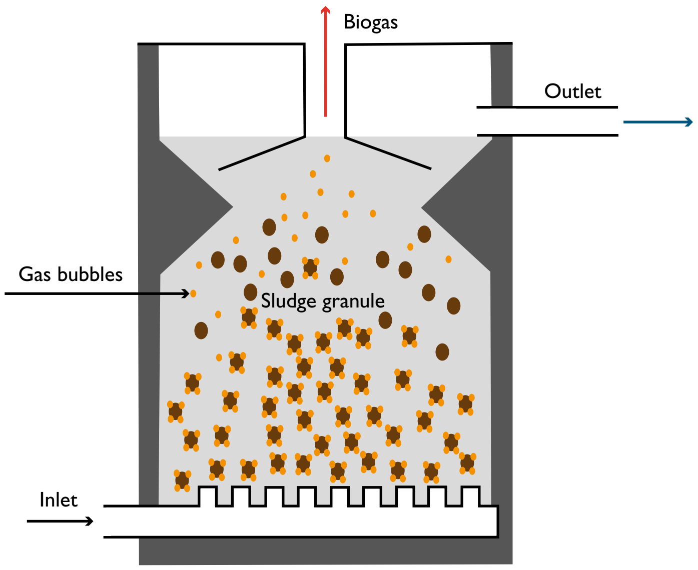
27 Usually in dairy farms the existing cow effluent storage tank is used.



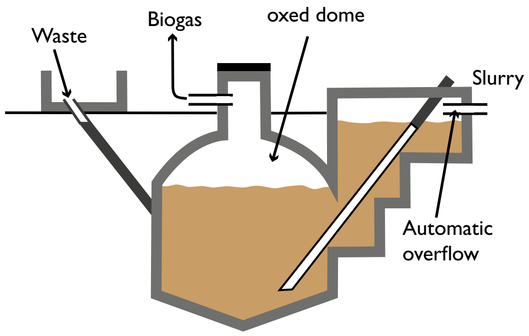
Bag digester: A durable flexible plastic bag is built above the ground in order to use sunlight as a heating source for the bag. As the biogas is generated, the bag inflates. It moves upwards and is extracted out of the bag through a pipe. Bag digesters are inexpensive and easy to transport but they can have relatively short lifespans compared with steel, concrete or fibreglass digesters. Bag digesters are not generally used for electricity production since the biogas yields are relatively low.



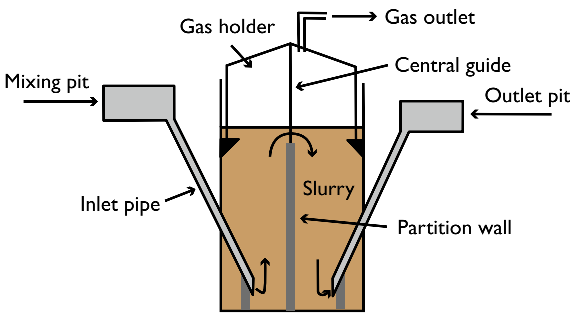
Up-flow anaerobic sludge blanket (UASB): The digester is filled with sludge and mixed by rising gas bubbles. The wastewater is introduced at the bottom of the structure and flows upwards into suspended sludge blanket filters to remove solids and provide contact with bacteria helping to digest the wastewater solids. The UASB technology is commonly used in wastewater treatment plants.



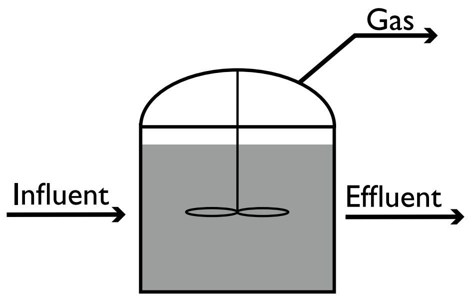
Fixed dome digester: The biogas is produced at the top of the digester, and the slurry from the bottom of the tank is displaced into a compensation tank (or expansion chamber) as the volume of the biogas increases. The fixed dome at the top of the structure does not have moving parts, which makes the technology relatively inexpensive. It can be almost completely constructed underground, which makes it suitable for colder areas.



Floating drum digester: This variation of the fixed dome digester consists of a gas holder, a gas outlet, a mixing pit, a feedstock inlet and outlet pipes, a partition wall, and a central guide. The gas-holding roof floats on the slurry or on a water jacket, and moves up and down with the volume of gas stored. The base of the digester can be built below ground level to avoid low air temperatures reducing gas production.



Complete mix digester: A temperature-controlled tank heats the feedstock to the optimal digestion temperature, and an electric-powered paddle mixes it with active micro-organisms already present in the digester. This method is the least common for small-scale household applications and expensive compared with other designs. With a relatively short retention time it best suits a more liquid feedstock (up to 15 percent DM) and is therefore suitable for commercial dairy applications. Complete mix digester: A temperature-controlled tank heats the feedstock to the optimal digestion temperature, and an electric-powered paddle mixes it with active micro-organisms already present in the digester. This method is the least common for small-scale household applications and expensive compared with other designs. With a relatively short retention time it best suits a more liquid feedstock (up to 15 percent DM) and is therefore suitable for commercial dairy applications.



Sources: Adapted from (1, 2) plugflowdigester.com; (3, 6, 7) FAO, 1992a; (4) grassrootswiki.org; (5) sgpindia.org.

COSTS

A small-scale (e.g. 250 kW_{el}), high-technology digester with a CHP is far costlier per kWh of energy output or per service provided than a large-scale tank, dome, lagoon or bag digester, where the biogas is directly combusted for heat without treatment or transformation. Decreasing the LCOE can be achieved by (i) the use of low-cost feedstocks that are available all year round such as organic wastes, rather than having to produce and store silage from green crops with high production costs; (ii) economies-of-scale from larger capacity plants with lower capital costs/kW; and/or (iii) efficently using the waste heat if a gas engine is employed. Typically, the more advanced the technology, the higher the installed cost but the lower the LCOE due to better overall efficiency.

Biogas-fuelled electric power generation systems have capital costs between US$2,570–6,100/kW installed (IRENA, 2013b). The costs can be as low as US$350 kW for simple household-scale digesters in developing countries (REN21, 2015; ESCWA, 2014) or as high as US$11,000/kW for high-technology plants in developed countries (Inagro et al., 2015). The LCOE ranged between US$0.06–0.19/kWh electrical output when assessed in 2012 and 2014 (IRENA, 2013b; REN21, 2015).

Maintenance costs may be significant in a biogas power plant. Maintenance is usually subdivided into three main categories:

(i) Engine maintenance;
(ii) Rest of the plant maintenance; and
(iii) Biological surveillance.

The rest of the plant maintenance refers to the maintenance of all the other mechanical and moving parts of the plant: pumps, solid screw conveyor, hydraulic valves, sensors, gas bubble, agitation system, compressors, greasing, and power plant cleaning. In the case study presented below, these routine tasks are performed by five skilled biogas workers who also take care of feedstock collection, feeding and power plant cleaning. Engine maintenance includes several programmed operations to maintain the engine at optimal running conditions (like changing spark plugs, cleaning and changing filters), and is done by the farm's mechanics.

Especially in biogas power plants that use mainly cow effluents, biological surveillance is usually performed at farm level given that the farm biogas operators have been previously trained for that purpose by the technology provider.

Only turnkey price and LCOE together can precisely characterize the financial performance of a biogas plant, since the nominal capacity (e.g. m^3 biogas/hour) does not determine the hours and effectiveness of its annual operation or the maintenance requirements that both impact the cost in terms of US$/$m^3$ biogas produced.

For example, a farm in Africa, using European-standard biogas technology, with 500 cattle and access to around 1,000 tonnes of crop residues and 5,000 tonnes of grass per year, would provide sufficient feedstock to supply a 250 kW_{el} biogas for power generation plant. The amount of biogas that can be produced depends on the amount and quality of cattle manure (solid or liquid), which in turn depends on the breed and type of animal, the average size, the farm management system, and the ability of the digester feed intake to handle adequate volumes of various feedstocks. An indicative range of financial attractiveness for generating electricity from biogas produced from cattle manure and crop residues was estimated to have an IRR of 3–27 percent.[28] At the household scale, it is not possible to express even an approximate cost with any validity in monetary terms.

MAIN IMPACTS

Biogas systems provide clean energy to dairy farmers and enable them to diversify their income, decrease dependency on imported energy sources, generate manure treatment and sanitation, and produce quality soil conditioner.

Commercial dairy farm biogas applications imply farm income diversification by several mechanisms:

- grid-connected biogas-fuelled electricity generation plants can sell excess electricity to the local provider at market prices or for a specific feed-in tariff (FiT), where offered;
- heat co-generated with the electricity can be used on-farm for heating water or buildings, to create process steam, or to power absorption refrigeration – thus decreasing the external energy demand for the dairy farm or milk processing plant; and

28 Based on the following assumptions:

- Manure production per head of cattle is 10 kg/day at 10–15 percent DM.
- No extra costs for water supply were included due to wastewater available for diluting the feedstock mix as necessary.
- The co-benefit of using the digestate produced in terms of nutrients and organic matter was not included. It could contribute to the long-term economic viability of agricultural production if a local application is foreseen, or provide additional revenue if a market for the digestate can be found.
- Energy content of methane is 36 MJ/m^3. Through a CHP, the efficiency conversion to electricity is 30–35 percent and 40–45 percent to heat. This equates approximately to 2 kWh (7.2 MJ) of electricity and 9 MJ of useful heat per m^3 of biogas with 60 percent methane and 22 MJ energy content (SGC, 2012).
- Some of the heat is used on site to maintain the temperature of the digester at around 35 °C.
- No extra profit was considered for heat sale or from any heat-derived cost savings.

- purified methane can be fed into the natural gas network, or compressed into cylinders and used in farm-vehicles, sold directly, or sold through a co-operated local fuel station.

Biogas is an alternative form of energy access that may help avoid food losses at the farm level in cases of unreliable power supply. Of course, since the installation of a biogas-to-energy plant is a medium or large energy intervention, it would also require some changes in the land use, which becomes significant if it relies on ad-hoc energy crops.

AD is an effective manure treatment method that upgrades manure and slurry into a digestate without decreasing the nutrient content (whilst eliminating most toxins and pathogens, coliforms in particular). The co-benefit is a valuable – and possibly marketable – organic fertilizer that can have positive impacts on soil quality and efficiency of fertilizer use, with a proven effect on productivity (Simon et al., 2015). However, if the digestate is not returned to the land, a soil nutrient deficiency can result.

For micro-scale household digesters, the biogas is normally used directly for cooking by direct combustion, therefore avoiding the cost of traditional cooking fuels (such as butane, coal, fuelwood, or charcoal), and the opportunity cost due to time spent in collecting fuelwood. The 10 kg/day of collectable manure from 1 adult grazing cow, if fed daily into an 8 m^3 dome digester, can typically produce up to 250 litres/day of biogas with enough energy to cook meals for 1 person throughout the year. If the cow is housed and feed is brought to her, more manure will be available for collection so that fewer cows can meet a family's cooking needs. If household wastewater and sewage is mixed into the digester, the digestate can still be used as biofertilizer. Adding crop residues can help produce more biogas if needed.

Commercial-scale biogas systems in remote areas require more labour than diesel-fuelled electricity generation systems per kW, which means that there can be a positive effect on rural employment (FNR, 2012). Apart from the construction phase, household digesters have little direct effect on employment.

Biogas can help decrease GHG emissions when it displaces unsustainable harvests of fuelwood, dung, or fossil fuels used for heating or electricity generation; reduces emissions from manure management; and avoids emissions from artificial fertilizer manufacturing. The replacement of fuelwood with biogas for domestic cooking also reduces local indoor air pollution, creating a healthier local environment (ESCWA, 2014).

Commercial-scale biogas plants need high-level engineering designs, and careful business planning and farm management to avoid significant fluctuations in methane output and to ensure a continuous and constant feedstock supply. For example, antibiotic treatment of the dairy herd might kill part of the methanogenic bacteria in the digester and hence decrease the biogas output, or even stop the digestion process.

It is often assumed that infrastructure investments are gender neutral, affecting women and men equally. However, this is rarely the case owing to their different roles and responsibilities affecting how they use and benefit from the infrastructure. A biogas power plant that improves access to energy without negative environmental implications is not likely to worsen gender inequality if women have equal opportunities to benefit from the more reliable energy supplies and employment opportunities.

TABLE 4.3. Advantages and disadvantages of dairy farm biogas for power generation systems.

Advantages	Disadvantages
• Significant decrease in methane emissions of the dairy chain by manure management, and by offsetting fossil fuels and fertilizers. • Waste management solution and improved sanitation. • Farm income diversification and decreased dependency on external power supply. • Access to more reliable power supply can reduce food losses. • Availability of surplus thermal energy, at commercial scale, that could be used for on-farm or milk processing operations. • Use of surplus biogas at household level can reduce indoor air pollution. • Digestate is a quality bio-fertilizer for local use or sale, generating income. • Digestate can displace chemical fertilizer consumption.	• High initial capital investment. • Risk of excessive freshwater use in case of dry feedstock or insufficient organic liquid waste. • Operation and maintenance require highly trained staff at commercial scale. • Some land required by the plant, usually productive land.

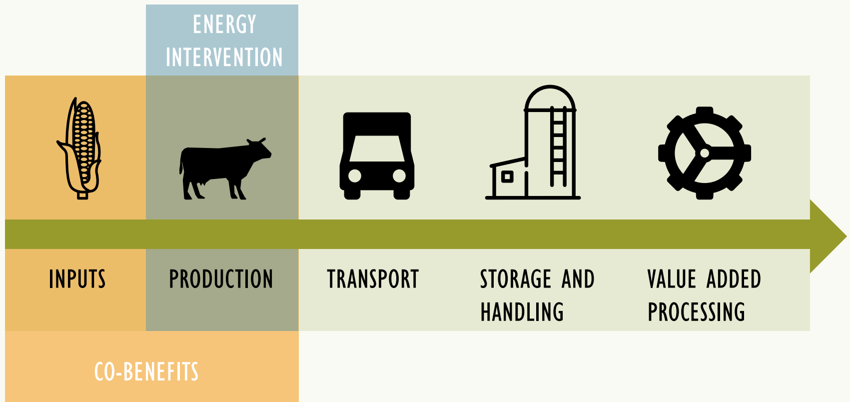
Source: Authors.

Source: © GIZ/JBO

CASE STUDY: BIOGAS FOR POWER GENERATION FROM DAIRY CATTLE IN KENYA

FIGURE 4.2. Intervention and co-benefits in the value chain.

Source: Authors.



Kilifi Plantations Ltd is a large agricultural company located in the south-east coastal area of Kenya north of Mombasa. It was established in 1920 as a sisal plantation and purchased privately in 1963 to continue as an agricultural business (Kilifi Plantation, 2016). The company owns and manages 2,500 ha of land to produce sisal, milk, beef, and vegetables (spinach, capsicum, okra, coriander, and tomatoes), mushrooms, watermelon, and maize. The main farm products are 350 tonnes/year of sisal fibre for export, and 3,000 litres/day of milk from 400 milking cows. As a major agricultural business, it pioneered biogas production for electricity generation. Using sisal plantation residues and cow manure as feedstocks, a medium-scale 750 m^3 complete mix biogas digester and a 150 kW_{el} CHP plant were incorporated into the farm operations.

Commercial dairy farming is practiced on both small and large-scale farms in Kenya highlands and lowlands, the latter including coastal province areas like Marakwet and Kikambala in Kilifi, and Matuga in Kwale where milk yields are relatively high. Overall, only around 20 percent of milk was produced on large- and medium-sized dairy farms with more than 100 cows in 2008, whilst 80 percent was produced on small farms (AHK Kenia, 2015). Larger dairy farms often keep their cows in a confined space over night to allow milking operations and have a refrigerated tank up to 10,000 litre capacity for collection, cooling and storage of milk. Most large dairy farms connected to the electricity grid have a diesel generator backup, although their power demand is relatively low (mainly for operating milking equipment and refrigeration plant) (AHK Kenia, 2015). However, if milk processing activities are performed on-farm, electricity demand can be significant. Off-grid dairy farms rely exclusively on diesel generators.

Feasibility analysis

Kenya's electricity grid is one of the most developed in sub-Saharan Africa. The country has high potential to scale up renewable energy technologies because of its abundant renewable energy sources. In spite of this potential, Kenya is facing an acute electricity shortage owing not only to limitations of installed capacity but also because more than 50 percent of Kenya's electricity comes from hydro power generation, threatening security of supply in times of drought (GTZ, 2010). Due to frequent power blackouts, the electricity supply companies must provide emergency power aggregates, thus increasing the overall cost of electricity, especially in the dry season.

Kenya has increased access to electricity to reach 23 percent of the population in 2012 (World Bank, 2016a). The majority of new connections occurred in urban areas. In rural areas, only 6.7 percent were connected, with two-thirds of the population still relying primarily on fuelwood (Heinrich Böll Foundation, 2013). Electricity tariffs in Kenya ranged from KES 7–13.50/kWh (US$0.07–0.14/kWh) in March 2017 for commercial consumers (Stima, 2017). In rural off-grid areas, electricity is usually provided by diesel fuel generators, exposing farmers to higher production costs for electricity with fluctuations due to variable fuel prices. For both on- and off-grid medium- and large-scale dairy farms, price fluctuations for electricity could be limited by using dairy cow manure to provide a reliable source of electricity. For on-grid farms generating electricity for their own consumption, any surplus could be sold to the national grid. They can gain access to Kenyan renewable energy FiTs under a contract with the grid operator, Kenya Power and Lighting Company (KPLC), which owns and operates the national transmission and distribution lines.

In an effort to promote the uptake of renewables, increase national electricity production, and promote smaller electricity projects, the Kenyan Ministry of Energy first implemented Renewable Energy Feed-in Tariffs (REFiT) in 2008 (Heinrich Böll Foundation, 2013). REFiT was revised in September 2012, differentiating into two groups: projects from 0.2–10 MW with a FiT of US$0.10/kWh in the case of biogas, and larger projects above 10 MW (Ministry of Energy Kenya, 2012).

To date, the FiT has not resulted in greater deployment of biogas for power generation projects since it is insufficient to guarantee a good return on investment. A minimum 100 KW generation capacity is needed to qualify for the FiT, and the electricity generated must be sold entirely to the grid (it is not possible to use part of it on-farm). Moreover, biogas producers have to pay for the costs for connection to the grid.

Description of the energy intervention

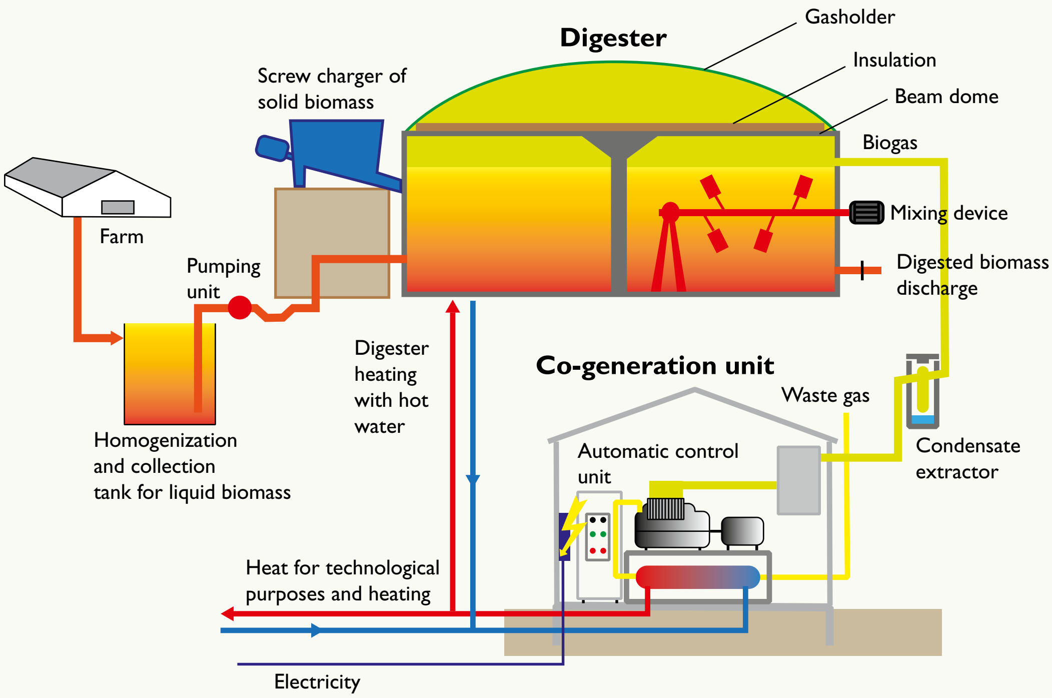
Since 2007, Kilifi Plantations has produced biogas for electricity and heat generation primarily to supply the on-farm electricity demand for sisal decortication to produce sisal fibre, as well as electricity demand for milking and milk cooling. Dairy cow effluent is collected, homogenized in a separate tank, and then automatically pumped into the 750 m^3 digester. Dairy cow dung, mixed with sisal pulp and food residues, have higher DM, so these are fed into the digester with a solid screw conveyor (Figure 4.3).

The biogas plant is operated by Biogas Power Company Ltd., a joint venture of Kilifi Plantations and the German companies *agriKomp GmbH* and *Schnell Zündstrahlmotoren AG and Co* (Energypedia, 2015).

The plant was built to help offset the high energy costs of Kilifi Plantations, which is currently US$0.21/kWh for the electricity purchased from the grid (Pers. Comm., 2017), or US$0.28–0.47 /kWh for the electricity produced using a diesel generator during power outages, which occur relatively often (AHK Kenia, 2014). As a commercial entity, the farm would buy electricity at a tariff of around US$0.15/kWh.

FIGURE 4.3. General scheme of the Kilifi complete mix biogas and CHP co-generation system.

Source: adapted from Kilifi Plantation, 2016.



The biogas plant was designed to fuel two gas engines providing 150 kWel total power capacity (75 kW each). However, the maximum output capacity has been limited to around 40 kWel in practice because the existing electrical line cannot carry sufficient current.[29] The two engines are therefore used alternately for electricity generation. The system is currently running on average 15 h/day. The solid feedstock is made up of sisal residues (12 tonnes/day) and manure from the 400 cows (2–3.5 tonnes/day mixed with food residues).

29 Source: Personal communication with Kilifi biogas plant technical manager (2016).

FIGURE 4.4. Biogas plant in Kilifi, Kenya: effluent storage tank, digester and shed containing the gas engine and generating plant.

Source: Authors.

A feasibility study considering an expansion of the plant to 230 kWel (with the addition of a third gas engine and generator with a capacity of 80 kWel) revealed that a FiT of US$0.12/kWh would be needed to cover the running costs (including depreciation of the plant) (AHK Kenia, 2014). However, to achieve an acceptable IRR of 18 percent and a payback period of less than 7 years, electricity sold to the grid would need a price of at least US$0.14/kWh (AHK Kenia, 2014).

If the plant runs at full capacity (140 kW_{el} assuming an efficiency of 93 percent compared to the nominal 150 KW capacity), 24h/day, it could generate around 811 MWh/year of electricity to be sold to the grid.

Financial CBA

Benchmark scenario

This CBA aims to illustrate the potential benefits for a dairy farm introducing a biogas for power generation plant using the case study experience of Kilifi Plantations. The CBA was conducted for the current situation (40 kW) and for the full plant capacity (150 kW nominal capacity).

Key factors for determining the profitability of a biogas project and the potential return on investment include share of on-farm electricity and heat demand met by local generation; purchase price of grid electricity; access to the grid for imports and exports of electricity; and FiT.

The present benchmark situation for a Kenyan dairy farm is that electricity is purchased directly from the grid or is generated on-farm with a backup diesel generator for when the grid electricity is not available.[30]

30 Typically, a 400-cow dairy farm in Kenya could produce enough biogas from the effluent to run a CHP plant generating between 400–500 kWh. If other co-feedstocks exist, as is the case for Kilifi Plantations (sisal residues), more biogas can be produced and hence more electricity (and heat) can be generated.

To assess the economic viability of a biogas plant, the following assumptions were made:

- **Discount rate:** A discount rate of 11 percent was assumed reflecting a recent 11 percent interest rate for Kenya 9-year Treasury Bonds, the 11.5 percent Central Bank of Kenya's official interest rate, and the 7.3 percent deposit interest rate.[31]

- **Life expectancy of the technology:** A well-designed and maintained digester has a life expectancy of around 20 years (Gebrezgabhera et al., 2010).

- **Scale:** The Kilifi power plant has a real capacity of 140 kWel, but the maximum power produced is 40 kW_{el} due to the limitations mentioned above. Both scales are considered for the financial CBA. The second scenario assumes that the electricity interconnection line has been upgraded and that the cost was not borne by the investor.

Costs

Capital cost: A total investment cost for the Kilifi 150 kW power plant was US$500,000. Other costs include grid connection, site preparation, project development, authorization and FiT agreement costs. Therefore, the total investment was US$570,000 (Table 4.4). In the case in which the plant runs at 40 kWel capacity, the cost of grid connection and FiT agreements are null. The study did not take into consideration the residual value of the plant after 20 years of life and, for simplicity, considered an upfront payment of the plant in full.

TABLE 4.4. Kilifi biogas for power generation plant: Installation cost assumptions.

Cost item	Cost (thousand US$)
Power plant acquisition (sourced from direct contact to Kilifi managers)	500
Grid connection (estimated) (for the 150 kW case)	20
Site preparation, including cement basements (estimated)	20
Project development, authorization, FiT agreement (for the 150 kW case)	30
Total investment	**570**

Source: Authors.

Maintenance cost: Replacement of worn or broken parts was envisioned to be US$10,000/year (personal com; Kilifi plant managers, 2016). Major engine maintenance after every 60,000–70,000 hours of engine running performed by the farm mechanics costs around US$20,000.

31 Data come from the Central Bank of Kenya statistics, retrieved online on June 2016 (https://www.centralbank.go.ke). However, the value of Kenya Bank's commercial lending rate from January 2015 to June 2016 ranged between 15–18 percent (http://www.tradingeconomics.com/kenya/bank-lending-rate). This analysis uses the lower 11 percent rate which reduces the value of future negative cash flows but reflects possible favourable financial conditions.

Operating cost: The operating costs for a large-scale biogas power plant are the labour needed to run the plant (two plant managers and five skilled workers were assumed), maintenance, spare parts, and feedstock purchase and/or preparation costs. It was assumed spreading of digestate on the land costs US$0.50/tonne. Water was assumed to be available at no cost.[32]

The average daily time taken for plant operation feedstock collection and feeding, digestate spreading (not a daily activity), daily plant maintenance and management was assumed to be about 8 hours/day on average. In the benchmark situation where workers only have to spread manure in the fields, fewer man hours per day are required.

The typical monthly wage of a Kenyan tractor driver is around KES[33] 6,890/month[34] (or US$815/year). This wage was assumed for each of the five skilled workers. For the two managers, a monthly wage for an Artisan Grade I of KES21,811/month (or US$2,578/year) was assumed. The total annual labour cost for the biogas plant was therefore US$9,231/year.

Since in this case the farm owns the land, no rental cost or land purchase was considered, nor any opportunity cost for alternative land use.

Benefits

The main direct benefits of the biogas for power generation technology system derive from the costs saved by not purchasing electricity and extra income gained from electricity sold to the grid. The biogas power plant currently runs for 15 hours/day. In the case of a 40 kWel capacity, the electricity produced cannot be sold to grid and is consumed on-farm. The Kilifi Plantation can thus avoid buying electricity from the grid and can use backup diesel generators[35] for about US$23,491/year.

In the case of a 150 kW capacity, the plant produces electricity for export to the grid at the Kenyan biogas FiT price of up to US$0.10/kWh. Selling all electricity to the grid at this rate would provide an annual revenue of about US$81,144/year, assuming that the engine has a 75 percent efficiency and the system runs 24h/day. The digestate is not commercialize, but used on-farm.

Financial profitability

As Table 4.5 shows, assuming the 150 kW installed capacity could be fully utilized, a financial NPV of about US$220,809 and an IRR of 4 percent can be expected after 20 years. The NPV is even more negative under current conditions of underutilization (about US$528,000). To get a positive payback within the investment lifetime of 20 years, the initial capital cost should be reduced by at least 45 percent.

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32 A feasibility analysis should ensure that there is sufficient water or liquid effluent to dilute any solid feedstocks.

33 The exchange rate used is KES1 = US$0.01.

34 http://www.wageindicator.org/main/salary/minimum-wage/kenya.

35 In Kenya, losses from power outages for utilities amount to 6 percent of total sales, which poses a real problem for the Kenyan economy (Eifert et al., 2005). Around 70 percent of firms in the country own backup electricity generators (Ramachandran et al., 2009). The ability of an enterprise to offset power fluctuations varies greatly by size. Only larger firms (with 100 or more employees) seem able to cope with Kenya's power crisis (Ramachandran et al., 2009). The electricity price from using the on-farm 25 kW diesel generating set as backup generation was assumed to be US$0.335/kWh (AHK Kenia, 2014). It was assumed that power outages occur on 80 days every year, with an average length of eight hours each (Ramachandran et al., 2009).

Additional co-benefits relating to the production of on-farm biogas that could be included in a CBA are:

- the surplus thermal energy from the gas engine, which if captured in a co-generation system could be used on-farm to e.g. heat water for sanitization of the milking plant and milk storage tank; and
- the digestate, which could be sold on the market, although currently a local market for the digestate does not exist. This will be considered in the economic CBA.

TABLE 4.5. Financial CBA (biogas for power generation).

Data	Unit	Plant running at partial capacity (current situation – 40 kW)	Plant running at increased capacity (150 kW)	Notes
Life expectancy of the technology	year		20	
		Financial costs		
Capital cost	US$	520,000	570,000	
Maintenance costs	US$/year	US$10,000/year for spare parts, US$20,000 for major maintenance (after 60,000–70,000 hours of engine functioning)	US$10,000/year for spare parts, US$20,000 for major maintenance (after 60,000–70,000 hours of engine functioning)	Pers. comm. Kilifi plant managers (2016)
Digestate spreading cost	US$/year	2,687	15,461	Assumption of US$0.5/tonne for spreading
Labour cost	US$/year	9,231	9,231	Two plant managers, and five skilled employees per year (Pers. comm. Kilifi plant managers, 2016)
		Financial benefits		
Own biogas electricity consumption	US$/year	23,491		Assumption: in the 40 kW case, 100% production is consumed on-farm. In the 150 kW case, 100% production is sold to the grid
Of which: Electricity savings from grid purchase	US$/year	18,131		Data from Kilifi plant managers
Of which: Electricity savings from diesel engine production	US$/year	5,360		Data from Ramachandran et al. (2009)

Electricity sold to the grid	US$/year	0	81,144
Financial profitability indicators			
NPV	US$	−528,194	−220,809
IRR	%		4

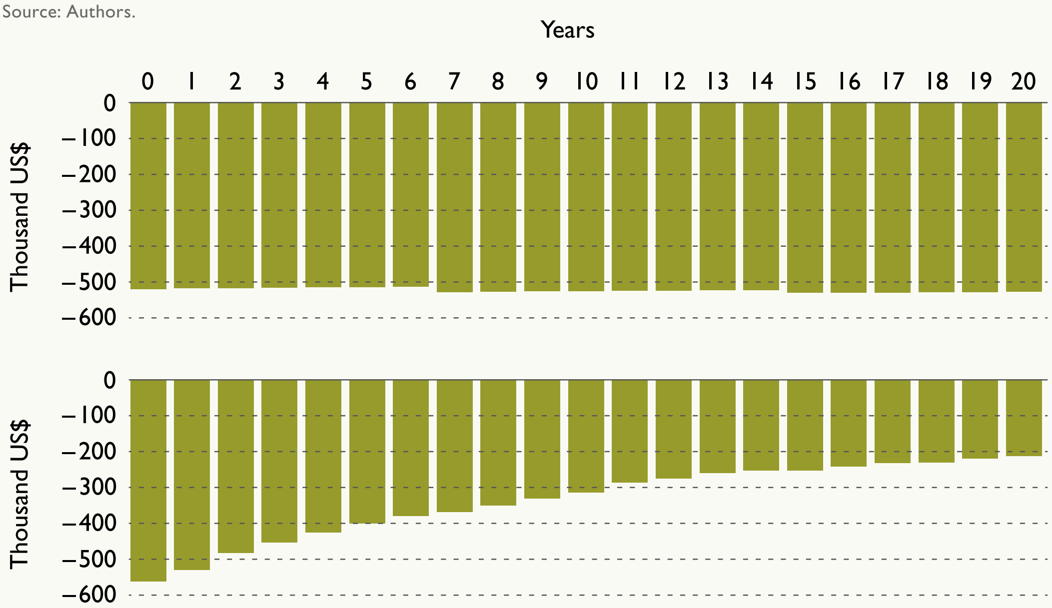
Note: A discount rate of 11 percent was adopted for the financial CBA.

Source: Authors.

FIGURE 4.5. Cumulative discounted net financial benefit (biogas for power generation) over 20 years: (i) current situation with plant running at partial capacity of 40 kW (top) and (ii) scenario at full capacity of 150 kW (bottom).

Note: Net financial benefits were calculated as the difference between the discounted benefits and costs of the case study and the benchmark scenario.

Source: Authors.



This current case study situation shows negative financial returns (Figure 4.5) because of the plant running at partial capacity due to restricted line carrying capacity. To run the plant at full capacity will require investments to upgrade the lines. Assuming the power utility, and not Kilifi Plantation, would make this investment, the financial returns to Kilifi would become more positive from a financial point of view. It is unclear why the line capacity was not checked as part of due diligence before investment in the biogas plant was made.

Economic CBA

Value added along the value chain

One main benefit of introducing biogas for power generation technology in a large-scale dairy farm in Kenya is that the farm no longer suffers from the unreliable electricity sources. Investment can have a positive effect on the avoidance of milk production losses when the electricity is used on-farm, and would reduce backup diesel power generation costs. Conversely, the government will lose diesel tax revenue.

Moreover, the dairy farm will become a new independent power producer in a rural area, and could contribute to the electrification of nearby rural communities, and enable the development of new businesses such as those linked to milk processing.

Subsidies and taxes

Unlike its neighbouring countries, Kenya does not subsidize electricity beyond the minimum subsistence level of 15 kWh/month. While this has led to a functioning and trustworthy utility, it also means that the additional costs of the FiT are largely passed on to all consumers. For this reason, the FiT is counted as a cost for society in the economic CBA.

The biogas technology and spare parts are imported from Germany and face import taxes. According to the Kenya Revenue Authorities (KRA, 2016), the initial plant with a capital cost of US$500,000 faced an import duty of US$15,000, consisting of an import declaration fee (IDF) and railway development levy (RDL),[36] payable on all imports into the country at 1.5 percent of the goods' customs value.

Similarly, spare parts with a value of US$10,000 are subject to import taxes of US$300. The import of engine components for the engine service after 60,000-70,000 hours of operation are valued at around US$20,000, and hence are subject to a duty of about US$1,500. All these import taxes are included in the economic CBA as benefits for society.

Conversely, the Kenyan government loses some tax revenue as a consequence of the displacement of diesel fuel to power backup generators. Fuel taxes per litre of fuel are around US$0.40 (The Star, 2016), so for a 25 kW generator consuming around 7 l/h, the government loss is around US$1,792/year.

Assessment of environmental and socio-economic impacts

Soil quality

The main impact of this energy technology on soil quality is from the digestate by-product of the anaerobic digestion process when used as a soil conditioner and fertilizer,partly substituting for synthetic fertilizers. Although the concentration of the N, P, K macro-elements in the digestate is fairly low compared to concentrated synthetic fertilizers, the nutrients are considerably more available to plant uptake than in the raw manure slurry. Before the introduction of the biogas system, the manure and liquid effluent would have been applied directly to the fields to improve soil fertility. Application of biogas digestate to the soil does not significantly increase the soil organic carbon compared to slurry direct application (our benchmark). The overall impact on the soil is therefore negligible (Eickenscheidt et al., 2014).

Impact	Relevance
Negligible	–

36 RDL was implemented to fund the construction of a standard gauge railway track.

Fertilizer use and efficiency

Given the assumption that synthetic fertilizers were used on the farm previous to the introduction of the biogas technology, and that part of these fertilizers would be reasonably substituted by digestate, the impact on the indicator measuring the amount and efficiency of fertilizer used will be positive.

There is no data available on the amount of fertilizers applied per hectare by Kilifi Plantation or impacts on the PFP. Given the size and variety of crops produced, this indicator is hard to accurately quantify.

The digestate is used on the fields as a substitute for chemical fertilizers. The benefit in terms of fertilizer use is assumed equal to the market price of digestate, i.e. US$2/tonne of digestate. Therefore, benefits from digestate use are about US$10,750/year for the plant working at 40 kW capacity and about US$61,845/year for the plant working at 150 kW capacity.

Impact	Relevance
Positive	High

Indoor air pollution

The biogas for power generation technology will have no direct impact on indoor air pollution because the biogas is directly used in CHPs to produce electricity, as in the case of Kilifi Plantations. However, if some of the electricity is available to displace cooking fuels or kerosene in workers' houses or on-farm, there is some potential to reduce air pollution.

Impact	Relevance
Negligible	–

Water use and efficiency

Water use could be an important issue if the feedstock used has high dry matter content and water is needed for dilution to aid the digestion process. In the case of large dairy farms, the mixed liquid and solid effluent slurry collected underneath the feeding area is suitable for biogas feedstock. Cow dung might come from the fields but will need a collection system. In the case of Kilifi Plantations, some water is regularly used for cleaning purposes but not to dilute feedstocks. Any increase in water use due to cleaning operations would be negligible.

Impact	Relevance
Negligible	–

Water quality

Digestate can potentially contribute to water contamination if discharged close to waterways. Considering that digestate may reduce synthetic fertilizer application, the N, P, K loadings in nearby water courses or groundwater could be lower than the benchmark scenario (assuming fertilizers were used). This also assumes an appropriate application of liquid digestate in the fields. If possible, liquid digestate should be applied using precision application equipment, such as band spreaders or shallow injectors. It should be incorporated rapidly into the soil to increase the amount of nitrogen available for crop uptake and to reduce the amount lost as ammonia (WRAP, 2016). The pH of the slurry coming out of the biogas plant should be monitored to minimize risks. In general, the effect of digestate on pollutant loading in water, water temperature and pH should be monitored.

Impact	Relevance
Variable	Moderate

Food loss

Biogas for power generation on a large-scale dairy farm has little effect on the avoidance of food production losses on-farm. Most large farms are equipped with diesel generators to avoid negative effects of frequent power outages on milk quality from lack of cooling.

A positive impact is improved access to a reliable source of electricity for other farms and residences in the area. However, this indirect effect is very difficult to evaluate as it depends mainly on the local grid, the locality of neighbouring farms, and their willingness to be connected to a local mini-grid.

Impact	Relevance
Negligible	–

Land requirement

There is no direct impact on land requirement unless energy crops are grown. Agricultural residues are normally used as feedstock as well as manure. The land area for the power plant depends on the technology used and the impact is limited (about 500 m^2 for a 150 kW plant). Moreover, that area is often not former agricultural land.

Impact	Relevance
Negligible	–

GHG emissions

The biogas plant contributes to reduced GHG emissions by displacing electricity from the grid and diesel generators, and by avoiding emissions from crop residues and manure. Using the respective grid and diesel generation emission factors for Kenya (IPCC, 2006), the avoided CO_2eq emissions amount to around 270 tCO_2eq/year.

The avoided GHG emissions can be monetized and included as benefits in the economic CBA (Table 4.7). The social cost of carbon (SCC) is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. This study assumes a SCC of US$36/tonne, though this exceeds current prices of around US$15–20/tonne in emission trading schemes. Based on this price, about US$9.7 thousand/year can be saved by the plant running at 150 kW capacity.

Impact	Relevance
Positive	High

Access to energy

Considering that the vast majority of large dairy farms are connected to the grid and equipped with backup diesel generators, the technology does not impact farm access to energy. A positive indirect effect could be the provision of a more reliable source of electricity for nearby households and farms, and hence a contribution to stabilizing the grid – which may become relevant at scale.

Impact	Relevance
Negligible	–

Household income

The introduction of a biogas for power generation technology on a large farm does not produce any direct increase of household income.

Impact	Relevance
No impact	–

Time savings

The introduction of biogas for power generation will not produce any effect on time saving at farm level.

Impact	Relevance
No impact	–

Employment

The introduction of a biogas for power generation technology has a positive effect on rural employment, since the plant will need to be operated by skilled workers and will need management. In the case of Kilifi Plantation, two biogas managers and five skilled workers were. Their annual wages amount to more than US$9,200/year.

Impact	Relevance
Positive	High

TABLE 4.6. Summary of environmental and socio-economic impacts.

	Indicator	Impact
	Soil quality	Negligible
	Fertilizer use and efficiency	US$61.9 thousand/year from digestate use
	Indoor air pollution	No impact
	Water use and efficiency	Negligible
	Water quality	Variable
	Food loss	Negligible
	Land requirement	Negligible
	GHG emissions	US$9.7 thousand/year in SCC avoided
	Access to energy	Negligible
	Household income	No impact
	Time saving	No impact
	Employment	7 employees; US$9,231/year

Note: green = positive impact, yellow = variable impact, red = negative impact,

Source: Authors.

Assessment of economic profitability

By producing electricity and selling it to the grid, the biogas plant competes with Kenyan electricity generators and grid operators. In Kenya, the cost of producing electricity is about US$0.03/kWh (Stima, 2017). If this cost is considered as a cost for society, the biogas plant introduces additional economic benefits. On the other hand, for each kWh sold by the grid operators, the government earns about US$0.02. This is lost when electricity is produced by the biogas plant – which hence can be considered as an economic cost.

As Table 4.7 shows, other economic costs include the FiT – representing a cost for society – and reductions in revenues from fossil fuel taxation. Total economic benefits include import duties (on machinery and spare parts), GHG emissions avoided, digestate use as fertilizer and employment creation. Assuming that the plant runs at 150 kW capacity, the economic NPV is more positive than the financial NPV.

TABLE 4.7. Economic CBA of the case study (biogas for power generation, 150 kW).

	Unit	Value	Notes
		Economic costs	
Feed in tariff	US$/year	81,144	Assuming US$0.10/kWh
Avoided tax revenue from fuel tax	US$/year	1,792	Assuming US$0.40/l taxation on diesel (The Star, 2016)
Avoided tax revenues from electricity generation	US$/year	16,229	Assuming US$0.02/kWh (Stima, 2017)
		Economic benefits	
Import duties on plant (US$500,000)	US$	15,000	Source: Kenya Revenue Authorities (KRA, 2016)

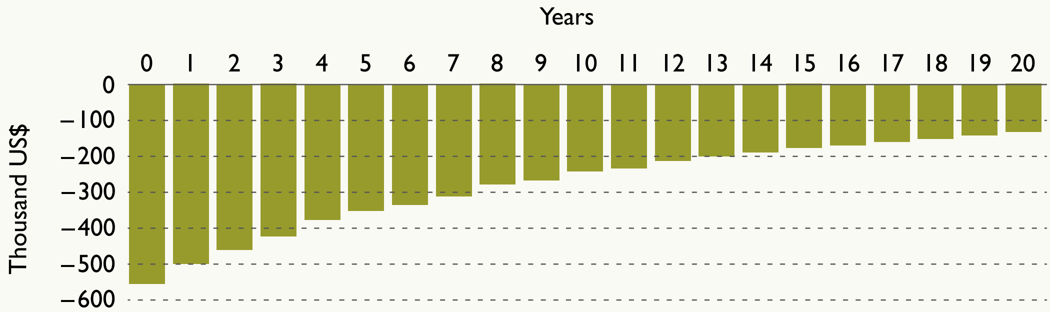
Import duties on spare parts (from Germany)	US$/year	300 for spare parts; 1,500 for major maintenance	Source: Kenya Revenue Authorities (KRA, 2016)
Avoided generation cost	US$/year	24,343	Assuming US$0.03/kWh (Stima, 2017)
Environmental and socio-economic benefits			
GHG emissions avoided	US$/year	9,707	270tCO_2eq/year considering a social cost of US$36/tonne
Digestate use as fertilizer	US$/year	61,845	Assuming value of digestate is US$2/tonne
Employment creation	US$/year	9,231	Two biogas managers and five skilled workers are employed
Economic profitability indicators			
NPV	US$	–140,641	
IRR	%	7	

Note: A discount rate of 11 percent was adopted for the economic CBA.

Source: Authors.

FIGURE 4.6. Cumulative discounted net economic benefits over 20 years (biogas for power generation, 150 kW).

Source: Authors.

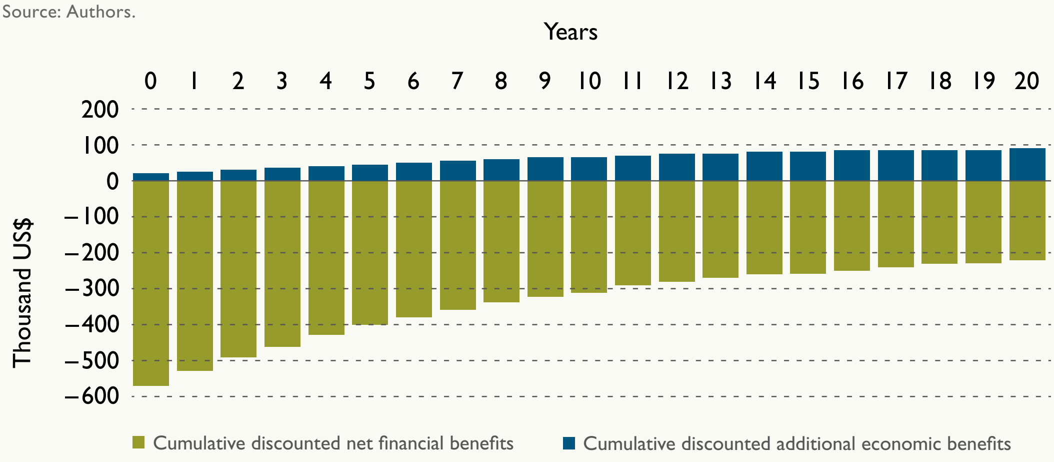


Results

Based on the current conditions and assumptions, the investment has a negative financial NPV, mainly due to the high capital cost and the technical limitations to utilizing the full capacity of the plant. If this last barrier could be overcome by upgrading the grid lines, the investment could have a more positive NPV – but the investment still does not pay back. In the economic CBA, the FiT and the lost revenues from fuel tax and electricity taxes were treated as costs; while import duties, reduced GHG emissions, digestate use, employment creation and avoided generation costs were accounted as economic benefits. The additional economic net benefits are positive, but not sufficient to offset the negative financial flows (Figure 4.7).

FIGURE 4.7. Cumulative discounted net financial and economic benefits (biogas for power generation, 150 kW).

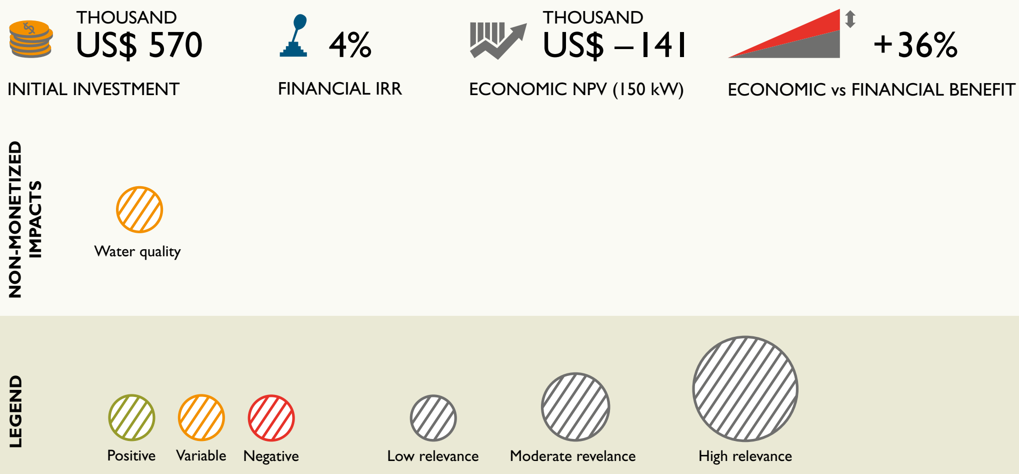
Source: Authors.



The impact on water quantity could be negative but is still negligible. Water quality must be checked for any specific biogas intervention, as it can be negative if the digestate is discharged on land close to waterways.

FIGURE 4.8. Key figures of the case study (biogas for power generation).

Source: Authors.



4.1.2. BIOGAS-POWERED DOMESTIC MILK CHILLER

Cooling milk directly after milking hampers bacterial growth substantially.
Source: © GIZ/Alex Kamweru

In remote locations where grid electricity is non-existent or unreliable, domestic milk chillers are an interesting option to extend the shelf life of milk, since milk spoils quickly in a warm climate, and cold-storage facilities are often absent (SNV, 2016). Off-grid technologies to chill small quantities of milk can be absorption chillers, either powered by biogas or by solar thermal. Other solar milk cooling technologies are described in the next section 4.1.3.[37] This section will first analyze costs and impacts of absorption chillers in general, and then apply the methodology to a case study of a biogas-powered domestic chiller in Tanzania.

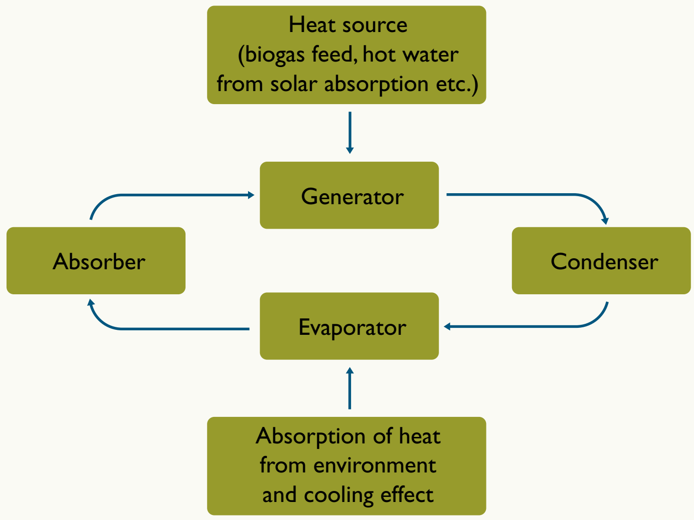
Absorption cooling is a well-known technology, although it is not common for household appliances. For instance, it is widely used for camping refrigerators. Absorption chillers are refrigeration units that are powered by heat instead of mechanical compressors, to provide the energy required for cooling. Typically, the heat is supplied as steam, hot water, waste heat or combustion of gas.

An absorption chiller is mainly based on four components, as illustrated in Figure 4.9: the generator, the condenser, the evaporator and the absorber. Both absorption and compressors refrigerators use a refrigerant, usually ammonia in absorption chillers. However, absorption chillers also make use of a low-pressure environment, which lowers the boiling point and hence the evaporation temperature required by the

37 Alternatively, it is possible to power milk chillers using PV technology backed up with batteries (see also 4.1.3). Considering the whole life of the investment, this technology may result in not being competitive, and hence is not investigated further. Other technological alternatives for household milk cooling include systems backed up by a thermal battery (see for example PROMETHEAN at http://modernfarmer.com/2014/02/chilling-cow/) or evaporative cooling systems (see for example THERMOGENN at http://www.smallholderfortunes.uga.edu/technology.html).

FIGURE 4.9. Absorption cooling cycle.

Source: Authors.



refrigerant. The refrigerant evaporates in order to absorb heat from the surrounding environment – in this case the inside of the chiller – and consequently generates the cooling effect. The gaseous refrigerant is then absorbed by a fluid, usually water or lithium bromide, in the absorber. To be efficiency, this process has to be cooled. A heat source is then applied to the generator to regenerate the absorption solution, so that the refrigerant evaporates from the absorbent fluid, and condensates in the condenser through a heat exchanger outside the system. The refrigerant then circulates by means of an expansion valve in the evaporator to restart the cycle (Mears, 2001; Solair, 2016). Absorption chillers move the refrigerant from the evaporator to the condenser, using pressure differences from hot fluids heated by an external source (e.g. solar thermal collectors or a biogas burner), hence no moving parts are required (no electric mechanical compressor) (Energy.gov, 2013).

A biogas milk chiller (BMC) can use burned biogas directly as a source of heat, or a heat transfer fluid such as hot water heated by biogas in a separate biogas-burning system. The cold energy generated by the absorption unit is stored in a thermal buffer and released when the milk cans are placed inside the BMC. It can therefore work without access to grid, thus significantly improving the opportunities for remote dairy farmers. For 100 litres of refrigeration volume, about 2,000 litres of biogas per day must be combusted, varying according to the outside temperatures (Energypedia, 2016).

Given the small size of household systems, biogas can be produced using manure and/or other agricultural residues as feedstock, by means of a fixed dome digester, a floating dome digester, or a bag digester. Regardless the technology chosen, the biogas produced inside the digester is used to run the cooling machine or/and power other appliances.

Biodigesters perform optimally under a frequent, regular feeding regime up to twice a day. Practice shows, however, that feeding only once every 2 days up to once a week does not disturb the methane-generating systems to the extent that installations stop working. However, if the process is stopped for more than about 3 days, the biogas production will be reduced due to a decrease of anaerobic bacteria. It would take several days to start up again.

As mentioned earlier, the biogas can be used for chilling. Surplus production can be used for direct combustion in stoves and gas lamps, as showed in Figure 4.10. The quantity of biogas produced by these systems is usually not sufficient to generate electricity to power other household appliances.[38]

FIGURE 4.10. Example of an integrated biogas-powered system for a domestic milk chiller.

Source: SimGas, 2015.

1. Manure from livestock	Each day a farmer feeds the digester with manure from livestock, and water.
2. Anaerobic digestion	Inside the digester, micro-organisms work symbiotically to convert the manure into biogas and slurry through the anaerobic digestion.
3. Piping	Biogas flows through piping from the digester to the farmer's house, where the pipe is connected to a cook stove and other biogas auxiliaries.
4. Milk chiller	Biogas can be used to power off-grid milk chillers to keep milk fresh.
5. Cook stove	Biogas stoves allow farmers to cook their meals using a clean fuel.
6. Biogas lamp	Biogas can fuel gas lamps used for both task and ambient lighting.
7. Organic fertilizer	Slurry that has been fully digested exits the system onto to the farmer's land where it is used as an organic fertilizer.

Solar thermal systems are an alternative to biogas-powered systems, and are particularly interesting for sunny regions. They harness solar energy for thermal energy use through solar heat collectors, which is then used for cooling. The two available types of collectors for this range of temperature are flat-plate or evacuated-tube. Tube collectors work better in colder and cloudier climates. Parabolic troughs can also be

38 More specific information on biogas generation systems can be found in Section 4.1 "Biogas for power generation".

used as thermal collectors to harness solar heat energy (FAO, 2016b). Using the heat for absorption refrigeration is a relatively new technology that avoids the use of an electric powered compressor. In the context of milk conservation, complete sets of small-scale portable cooling systems exist. The use of solid refrigerants and local, non-precision components enable production at a low cost with low-maintenance technology (PAEGC, 2016b).

COSTS

An absorption chiller system is composed of three main components:

(i) The solar collectors or the anaerobic digester;

(ii) A fluid circulation system;

(iii) The absorption chiller itself, which may be equipped with a burner if the heat is provided by direct combustion of biogas.

The absorption refrigerators require little maintenance since they have no moving parts and are relatively inexpensive in large quantities. Residential scale absorption chillers can be purchased for as little as US$550 (Carlson et al., 2014).

A complete solar absorption refrigeration system was designed by the University of Santa Clara in California, taking into account the needs of small-scale rural villages located off-grid. For this system, a refrigerator operating temperature of 4 °C was considered, with the size of a traditional mini fridge. The costs of all components of the systems, including the solar tracker, the solar receiver, the fluid circulation systems and the absorption chiller, accounted for about US$5,000. The estimated mass manufacturing cost could potentially be reduced to around US$700 (Carlson et al., 2014).

Considering an absorption refrigeration system running on biogas, the expected price for a system including a digester, stove, piping and installation is in the range of US$2,000–4,000 for systems with a digester size of 4–8 m^3.

MAIN IMPACTS

Absorption chillers have lower efficiencies compared to compression chillers and may require skilled maintenance due to the complex inner functioning. Nevertheless, an absorption milk chiller is a good alternative when waste heat or an alternative low-cost energy source is available, as in the case of manure on dairy farms (Aserud, 2012).

Even though absorption chillers are not as efficient as chillers using mechanical compression, they have advantages to offset the lower efficiency in many cases (Mears, 2001). The greatest advantage of this technology is its capability to be installed in areas that are off-grid, therefore providing a service (milk refrigeration) that would not be available otherwise. In fact, a vast majority of currently available chilling facilities are diesel-powered. Alternatively, milk is not cooled down at the farm level, reducing the usability of evening milk to self-consumption. Solar-thermal or biogas absorption chillers represent a solution to avoide milk spoilage.

Some of the benefits of these technologies are increased loyalty of customers for milk delivery, increased intake of evening milk, improved quality of collected milk, reduced milk rejection and consequent increased utilization of installed processing capacity. Renewable energy-powered absorption milk chillers may help small dairy farmers to meet quality standards required to access the formal sector, increasing the farmers' income. In addition, with a milk chiller on-farm, milk delivery to collection centres can be reduced from several times a day to only once a day, resulting in time savings (SimGas, 2016).

Nevertheless, absorption chillers that run on biogas are still in a developing phase. A BMC would use readily available manure as its main feed source, reducing the need for an external source of power such as fossil fuels, and adding value to manure through anaerobic digestion. Manure, in fact, will generate both power and digestate, as residue of anaerobic digestion, which can be used as organic fertilizer – thus reducing the use of chemicals and hazards on soil (WISIONS, 2014a).

Additional GHG reductions come not only from replacing diesel with biogas but also from preventing manure from decomposing and emitting methane and nitrous oxide into the atmosphere.

On top of milk cooling, using biogas for other applications such as cooking considerably reduces indoor air pollution by replacing conventional solid fuels.

Nevertheless, the process of biogas production from manure must be kept going every day to keep the anaerobic flora well fed. If the process is stopped for more than approximately 3 days, the biogas production will be reduced due to a decrease of anaerobic bacteria. For this reason, it takes several days to start up again. Water is also needed in order to obtain a mixture suitable for digestion. For cattle waste, the 2:1 waste to water mixing ratio is demonstrated to be optimal for biogas production from methane-generating systems (Adelekan and Bamgboye, 2009).[39]

Finally, absorption chillers are relatively quiet operations because they have no mechanical compressor and only a few small liquid pumps. Larger gas-fired absorption chillers have one or more burner fans and some combustion noise, which is insignificant compared to the noise from a unit with a mechanical compressor (Mears, 2001).

Finally, since the technology is relatively new, it will require support services and skilled technicians for maintenance and installation. This may generate indirect quality employment.

39 Precise mixing ratios depend on the DM content in the dung (depending on quantity and quality of fodder and water intake of the animal), the hydraulic retention time, and the temperature. Literature indicates an optimum ratio at 8–10 percent DM. Assuming a DM content of 15-20 percent for cattle in Africa, a 1:1 mixing ration would also be acceptable and easier to implement.

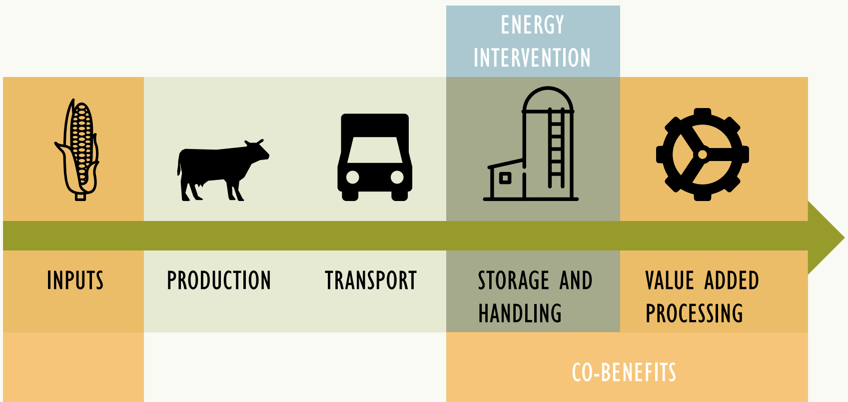
TABLE 4.8. Main advantages and disadvantages of biogas-powered domestic milk chillers.

Advantages	Disadvantages
• Access to energy • Milk conservation is enabled in off-grid areas thus reducing milk losses • Time saving due to fewer trips to the milk delivery point • Improved household income • Reduction of dependence on fossil fuels (diesel) • Potential use of biogas digestate as organic fertilizer • Reduction of noise compared to compression refrigerators • Excess biogas can be diverted to other uses (cookstoves, lamps, etc.) • Reduction of indoor air pollution • Reduction of GHG emissions from manure • Employment	• Absorption refrigerators have lower energy efficiency compared to conventional ones • Absorption refrigerators are complex systems, therefore more difficult to repair and maintain • BMC is still in the R&D phase and commercial solutions are very limited • AD must be kept going all times, requiring continuous work • Digesters must be kept at a certain temperature, therefore unsuitable for locations with high thermal excursion • Water is needed for AD of manure (2:1 waste to water ratio)

CASE STUDY: BIOGAS-POWERED DOMESTIC MILK CHILLER IN TANZANIA

FIGURE 4.11. Location of the intervention and co-benefits of biogas-powered domestic milk chiller in the value chain.

Source: Authors.



SimGas is a company based in the Netherlands and East Africa which designs and produces clean and affordable energy as well as sanitation solutions for rural areas based on biogas. The biogas systems are modular and can be installed in 2 days. The biogas is primarily used for cookstoves. However, in a consortium with SNV Netherlands Development Organisation, Mueller BV and BoP Innovation Center, SimGas is currently developing a biogas-powered domestic milk chiller.

In 2012, SimGas Tanzania Ltd. started the local production of biogas digesters, and since then have sold over 1,500 in Tanzania and Kenya (Pers. comm. SimGas, 2017). In addition, biogas-powered devices were developed by the company for cooling, cooking and charging other appliances. They include a low-voltage biogas-to-electricity device that was tested in Tanzania and Bangladesh; a biogas stove with a low-voltage socket; and a biogas milk chiller.

The digester and the cookstove have been commercialized while the milk chiller is at the demonstration phase. SimGas is currently testing the biogas milk chiller in a pilot project involving 15 farmers in Eldoret, Kenya and in Tanga, Tanzania (Pers. comm. SimGas, 2017).

Feasibility analysis

The dairy sector in East Africa includes more than two million smallholder farmers (SimGas, 2015). It is estimated that only 15 percent of the total milk produced in this area reaches the market, and 30–50 percent is not delivered to a milk cooling centre (MCC) but is consumed by the farmer's family, fed to calves, or wasted. Raw milk can rarely be cooled at farm level since 85 percent of rural East Africa lacks access to a reliable power grid (SimGas, 2015). It is estimated that in Tanzania about 70 percent of the milk produced is consumed or lost at farm level (TAMPA, 2013).

Only about 12 percent of the 2.5 billion litres of milk produced in Tanzania each year is sold through small-scale milk traders and collective bulking centres (Ministry of Livestock and Fisheries Development Tanzania, 2015). In the country, there are currently about 80 milk processing plants handling 167 thousand litres of milk daily. The plants range from many micro processing units that handle very small volumes to big centres with a capacity of about 60 thousand litres per day. However, more than 60 percent of the installed capacity of processors is currently not utilized.

Usually, dairy farmers have problems delivering their evening milk to the local dairy cooperative, MCC or market. The raw milk is therefore kept overnight at ambient temperature or, when electricity is available, stored in a refrigerator to be delivered in the next morning to the cooperative, MCC, traders, hawkers, or directly to local households. However, it usually takes about 22 hours to chill 10 litres of fresh milk to 4 °C in a refrigerator, so the cooled milk does not comply with international cooling standards.[40] Moreover, many farmers do not have refrigerator systems and, even if they do, the grid electricity is often unreliable with frequent outages, which occur most often during the night. Some farmers cool the milk in cold water baths or even hang the milk churns up in trees to be cooled by the wind.

In Tanzania, most milk is sold raw and unprocessed through informal marketing channels, such as to consumers in the immediate neighbourhood. Milk purchased by traders or their agents is often sold to consumers without prior processing or packaging. In this informal market, usually there is no formal testing of milk quality

40 Fresh milk is about 37 °C, which is an optimal temperature for bacteria growth. International standards require it to be chilled to 7 °C preferably immediately or within two hours after milking (Sun et al., 2011).

other than a simple smell check to verify whether the milk has turned sour. If it tests positive, the milk is rejected. Milk of better quality does not receive a higher price, with the exception of a very few dairy cooperatives that pay quality premiums (Pers. comm. SimGas, 2016).

In this context, a clean energy technology that can provide off-grid milk chilling on a micro-scale for farmers with up to 10 dairy cows (representing more than 80 percent of all dairy farmers in East Africa), and that allows the farmers to keep their raw milk fresh throughout the night (thereby complying with international milk cooling standards) would reduce milk losses, and enable farmers to meet the quality standards required by formal markets.

In Tanzania, smallholder dairy farmers typically run integrated farming systems in which farmers have both cattle and crops. SimGas considered that a biogas digester would be fed with manure already available locally and the resulting digestate would be a co-product used as organic fertilizer.

Adequate water supply needs to be available as a pre-requisite for operating a biogas system.

Description of the energy intervention

SimGas currently offers the "GesiShamba" biogas system:[41] a modular fixed dome rural biogas system, mass produced in high density polyethylene (HDPE) for small-scale farmers, small enterprises, and institutions such as schools.

The biomass feedstock is cow manure since this resource is easily accessible for dairy farmers. It may have to be mixed with water between 2:1 and 1:1 to produce slurry, depending on the local circumstances (SimGas, 2016). For optimal biogas production, the digester should be fed daily, which takes approximately 15 minutes for the farmer. Once the digester has been installed and some feedstock introduced, it takes on average 40 days to become fully operational (i.e. the hydraulic retention time is around 40 days).

The main benefit of introducing the BMC technology is improved milk quality and less spoilage. The CBA conducted here focuses on the milk chiller application, but also considers co-benefits from using biogas cookstoves and the digestate.

Digester

SimGas manufactures a fixed dome digester with a gas holder and an expansion chamber on top. The off-the-shelf digesters are mass-produced in HDPE and consist of multiple parts, creating a modular system that is scalable from 3 m^3 up to 12 m^3, in 1 m^3 increments depending on the size of the farm (minimum 2 cows) and depending on the demand for biogas by the household. The device is weatherproof, equipped with a gas-tight seal to avoid biogas leakage, and has an expected life of 20 years (SimGas, 2015).

41 Gesishaba means "farm-gas".

The weight of the tanks ranges from 100 kg for a 3 m^3 digester to 300 kg for a 12 m^3 digester. The multiple parts are stackable for efficient transport. Compared with a digester built from bricks and cement, installation takes days instead of weeks (two-day installation by trained technicians), and the system can be disassembled, moved and reassembled at a new destination.

About 30 litres of biogas can be produced from each litre of cow manure. For a farm of 4–6 cows (cross breed, zero grazing), a 6 m^3 digester with a 40-day retention time can take daily around 150 litres of slurry (100 litres manure, 50 litres water) to produce approximately 2 m^3 of biogas per day. This is sufficient to fuel a two-burner cook stove for about 3 to 5 hours, plus cooling up to 10 litres of milk per day.

Milk chiller

The BMC (Table 4.9) uses absorption cooling that, depending on the relative sizes of the digester and the milk chiller, can cool between 2.5 and 10 litres of milk.

TABLE 4.9. Technical details of the SimGas biogas-powered domestic milk chiller.

Milk tank capacity	Up to 10 litres per day *(capacity of 10 litres used for calculations)*
Dimension	Tank divided into 2 containers, each with a capacity of 5 litres
Rated capacity	Within 3 hours the raw milk is cooled from 35 °C to 4 °C
Cleaning	Manual
Biogas consumption	1,000 litres biogas per 10 litres of milk per day

Source: SimGas, 2015.

FIGURE 4.12. SimGas biogas milk chiller.

Source: SimGas B.V.

In Tanzania, purchasers of the digester are mainly:

- small dairy farmers with local cow breeds that produce a small quantity of milk for on-farm consumption and also provide meat; and

- larger scale farmers with more cows who sell milk to MCCs or rural markets. Typically, the herd is a mix of local and European breeds to give higher volumes of milk (Pers comm., SimGas, 2016).

If evening milk needs cooling, BMC shows a positive energy balance because the per-head production of cattle dung can generate sufficient energy to cool down the milk produced per-head, leaving surplus gas for other applications such as cooking. SimGas advises farmers, who want to cook meals and cool milk using biogas, to provide sufficient space for a 6 m^3 digester and to ease the collection of manure from a minimum of four heads of crossbreed cattle by housing them in zero-grazing units (SimGas, 2015).

Financial CBA

Benchmark scenario

The CBA was performed at household level and aimed to demonstrate the potential benefits for small-scale dairy farmers. The investment decision depends on income and any alternative options for a small dairy farm to cool and sell its milk. Farmers producing milk for their own consumption are less likely to buy a milk chiller than farmers selling milk to the market or MCCs, regardless of the technology's potential benefits. For simplicity, this CBA assumed an average herd size of three cows producing about 20 litres of milk per day (morning milk plus evening milk). Morning milk does not have to be cooled because it is delivered to the milk collection centre with cooling facilities available shortly after milking. It would only be needed to cool evening milk overnight, which then would be delivered together with the morning milk in the next morning.

The benchmark situation before the introduction of a SimGas BMC is "no milk cooling" since alternative solutions are not available at this scale that can cool fast enough to keep the milk fresh and maintain its quality till the next morning.[42] Standard domestic refrigerators cannot cool milk quickly enough, and a milk chiller powered by the electricity grid requires a reliable source of electricity, which is not available in rural areas of East Africa (UNDP, 2016). It is assumed that all morning milk reaches the market whereas evening milk would be rejected at the MCC the next morning and could therefore not be sold – since evening milk has to be stored overnight at ambient temperature resulting in increased bacteria growth. As a result, at least one-half of the daily milk production has to be consumed by the farmer's family, used to feed calves or other farm animals, or sold to neighbours at a low price. This situation is common in rural East Africa where only a small part of the population has access to electricity.

42 A current practice used by many farmers is putting milk cans in a cold-water bath overnight or hanging cans in trees to be cooled by the wind.

The following assumptions were made in the CBA:

- **Interest rate:** A discount rate of 16 percent was assumed reflecting a recent 16.5 percent interest rate for Tanzania 10-year Treasury Bonds, a 16 percent interest rate charged by the Bank of Tanzania on bank loans and a commercial lending rate of between 14–17% (Bank of Tanzania, 2015).

- **Life expectancy of the technology:** A 10-year life for the biogas milk chiller reported by SimGas was assumed although, being at an early stage of development, this could not be verified. Minor maintenance is envisioned every year to replace the pellets in the filter used to remove H_2S from the biogas to avoid corrosion, leading to a shorter life. For the biogas digester, the life expectancy of the recycled plastic HDPE material was assumed to be 20 years.

- **Scale:** A digester of 6 m^3 volume producing about 2 m^3 of biogas per day was chosen from the available range. Assuming that only the evening milk needs to be cooled, there would be sufficient surplus biogas to fuel a two-burner cookstove for a couple of hours per day. The SimGas BMC requires 1,000 litres of biogas per day (with an energy value of around 25 MJ) for cooling 10 litres of evening milk. Fuelling one or more cookstoves for a 1.5–2 hours/day also requires 1,000 litres of biogas.

Costs

Capital cost: SimGas digester prices vary with the size of the digester. Currently, the biogas milk chiller is still in the development phase with proven working models in the field. However, a market price has noy yet been established. A reasonable assumption is US$600 for a 10 litre biogas milk chiller, including installation, piping, user training and a two-year service agreement, assuming that the product is fully paid upfront. The biogas milk chiller can be connected to an existing operational biogas digester, or to a new biogas digester offered by SimGas priced at US$1,000 for a 6 m^3 digester, including a cookstove, installation, piping, user training, and a five-year full service agreement, assuming the product is fully paid upfront.[43]

Operating cost: The milk chiller does not have any operating costs. No additional cows are required and no additional cost is involved for feeding the cattle producing the manure. Around 15 minutes/day are required to feed the digester – but assumed at no extra financial cost. It is further assumed that the water needed to dilute the manure and cleaning the plant is freely available but could involve labour for collection.

Maintenance costs: Technicians deliver and install the biogas digester, connect piping to the biogas stove and biogas milk chiller, train the customer how to use the products safely and how to optimize biogas production. The company covers service during the first two years, later maintenance is minimal. The CBA assumes that the cookstove is replaced every 5 years for US$15, and that the milk chiller is replaced after 10 years for

43 SimGas provides different payment schedules over time to overcome the high installation cost. For a 6 m^3 digester the average payback time is 17 months (SimGas, 2015). Customers pay an initial deposit, followed by a monthly repayment schedule tailored to their needs. Various repayment plans are available, but in the CBA full upfront payment was assumed.

US$600.[44] Minor maintenance of the milk chiller is envisioned every year, and together with replacing the pellets for the H_2S filter (US$20), the total maintenance costs after 5 years are assumed to be US$35.

Operating time: The daily time dedicated for morning and evening milkings, cleaning the milk chiller, feeding the churns, collecting water, and cleaning the cow pens is three to five person-hours per day. In the benchmark case, about two to three hours are needed for milking and cleaning away the manure. For the financial CBA, a monetary value for the working hours is based on the minimum hourly wage for agricultural services in Tanzania.

The time spent collecting charcoal or fuelwood for the benchmark cooking situation is avoided by having the biogas cookstove. In the financial analysis, the time saving benefits for women and children are not monetized, since it is assumed for simplicity that the charcoal and fuelwood is purchased and not collected. Monetizing this time and labour would double count the time saving benefits discussed in the economic CBA (see below).

Labour costs: Small dairy farm family businesses do not hire additional employees. To monetize the operating costs, the minimum hourly wage for agricultural services is used: Tanzanian shilling (TZS) 512.85/hour (US$0.23/hour).[45] The hours spent operating the biogas plant are thus considered an opportunity cost since the farmer could have spent those hours on another productive, wage-earning activity.
Also, because milking has to be done every day, it is assumed that farmers work 365 days/year. The SimGas system creates an additional 0.5–1 hour of labour each day compared to the benchmark scenario, giving an additional cost of about US$84/year. Additional time would in fact be needed to clean the milk churns, feed the digester, operate the milk chiller, put two milk churns inside the chiller in the evening and take them out in the morning.

Land costs: It is assumed that the farmers own their land, therefore no rental cost is included in the analysis.

Benefits

A direct benefit of the technology is better quality milk and increased quantity for the market.

Milk price: The average farm gate price of raw milk in the Tanga region of Tanzania since 1 February 2014 is TZS673/litre (US$0.31/litre). There is no price premium for milk of better quality.

Milk sold: In the benchmark situation, only 50 percent of daily production can be sold on the market (the morning milk). For Tanga region, SimGas estimated that family and calf consumption of milk is around 30 percent. Assuming that with the BMC around

44 A prototype 10 litre milk chiller, including installation, training, piping, and two-year full service has an estimated total price of US$1,000 for the current hand-produced design. Here, a capital cost of US$600 is assumed since SimGas aims to reduce this cost via mass production (Pers. Comm., 2016).

45 Trade Union Congress of Tanzania, 2016. Exchange rate of 12 April, 2016.

30 percent of evening production is consumed by the farmer's family and calves, the remaining 7 litres can reach the market – together with 7 litres of morning milk.

Thus, at US$0.31/litre milk, farmers could earn an additional US$2.17/day by chilling the evening milk.

Co-benefits:

- Energy savings and/or time saved in collecting the fuelwood for the traditional cook-stove: SimGas estimated that the avoided fuelwood use is 7 tonnes/year for each household giving a savings of about US$250,650/year. In the benchmark, women and children dedicate between 2–4 hours/day to collect fuelwood, which can be spent on other activities related to operating the biogas system. In the financial CBA, it is assumed that the benefit from avoiding purchasing fuelwood is a conservative estimate of US$250/year.[46]

- Digestate use as an organic fertilizer: The value of the digestate in terms of increased crop yield and improved soil quality could not be easily quantified. A SimGas study on the effect of bio-slurry compared to no bio-slurry estimated that the crop yield increase ranges from 25–200 percent, resulting in a US$34/month estimate. Therefore, a benefit from digestate use of annual US$408/household is assumed.

- Health benefits: Biogas is a clean cooking fuel and removes the health hazards of indoor air pollution (accounted for in the economic CBA).

- Creation of technical employment for maintaining the milk chillers (accounted for in the economic CBA).

Financial profitability

Table 4.10 shows that both the financial NPV and IRR are very positive, and Figure 4.13 shows that the investment would pay back within two years.

46 It should be noted that milk refrigeration and cooking both rely on the same amount of biogas made available by the digester. While the biogas consumption of the milk chiller is predictable and stable, biogas consumption for cooking can vary significantly. It is therefore important that the digester is sized properly to match the needs of the household and that biogas consumption for cooking is wisely managed.

TABLE 4.10. Financial CBA (biogas-powered domestic milk chiller).

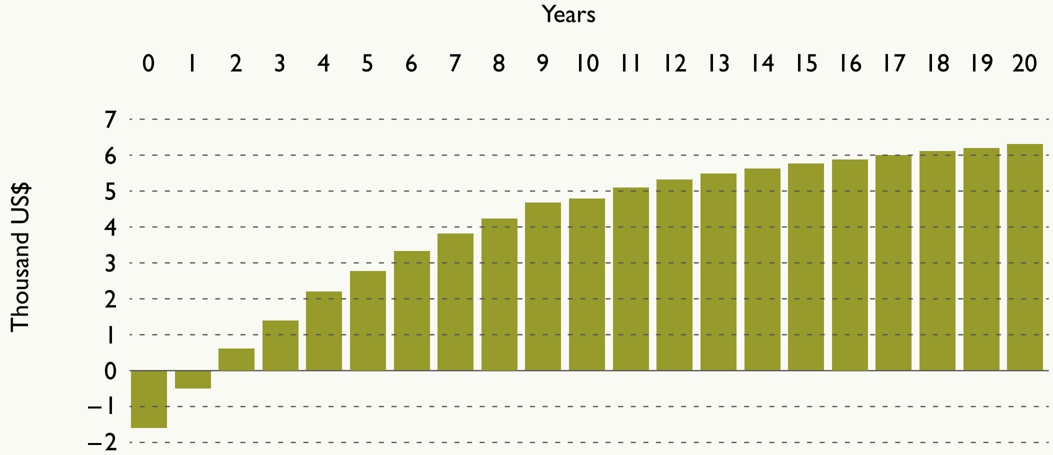
Data	Unit	Value	Notes
Life expectancy of the technology	year	20 for the full biogas system, 10 for the milk chiller	Pers. comm. SimGas
		Financial costs	
Capital cost	US$	1,600	Assumption for a 6 m³ digester, milk chiller, stove, installation, piping, training and 2 years of full service
Maintenance costs	US$/year	US$15 every 5 years for cookstove + US$20 every year for pellets for milk chiller + US$600 for replacing the milk chiller at year 10	Pers. comm. SimGas
Operating costs	US$/year	126	
Cow feed	US$	No change with or without BMC technology	
Water	US$	0	Pers. comm. SimGas
Additional operating time	h/year	365	Assumption of one hour every day
Additional labour cost equivalent	US$/year	84	Minimum wage of US$0.23/hour (Trade Union Congress of Tanzania)
Additional land cost (rent)	US$/ha/year	0	Farmer-owned land; no opportunity cost
		Financial benefits	
Additional income from milk selling	US$/year	792	Assuming 8 additional litres sold per day to the market (from evening milking)
Additional income from increased yield due to use of digestate	US$/year	408	Pers. comm. SimGas
Health benefits due to cookstove			
Savings on fuel per year	US$/year	250	Pers. comm. SimGas
		Financial profitability indicators	
NPV	US$	6,271	
IRR	%	85	

Note: A discount rate of 16 percent is assumed (Source: Bank of Tanzania). This analysis assumes that the dairy farmer pays for the SimGas system in full at year zero.

Source: Authors and sources as indicated in Notes column.

FIGURE 4.13. Cumulative discounted net financial benefits over 20 years (biogas-powered domestic milk chiller).

Source: Authors.



Economic CBA

Value added along the value chain

Cooling milk on-farm will result in a higher supply of evening milk to the dairy cooperatives (or farmer groups). These cooperatives will become more economically viable due to improved spread of capital costs based on a higher utilization rate. More milk collected at the cooperatives results in increased milk transport to the milk processors which, in turn, increase the utilization of their installed processing capacity.

In Tanzania, the typical milk price at the farm gate is US$0.31/litre while the full retail price is over US$0.85/litre.[47] The value added from cold storage, packaging, transport and distribution is the difference between the value of the output and the cost of the inputs. In 2012, the cost to process 1 litre of milk was about US$0.73/litre (TZS1,560), while the price of cultured (packaged) milk was about TZS2,000 (Table 4.11). Hence, the value added for processed milk was about TZS440/litre.

47 Source: http://www.numbeo.com/cost-of-living/country_result.jsp?country=Tanzania.

TABLE 4.11. Value-added costs for 1 litre of processed milk in Tanzania in 2012.

Cost item	TZS	%	US$
Raw milk on farm	738	38	0.31
Labour	94	6	0.05
Rent of land	26	2	0.01
Water and electricity	374	24	0.19
Administrative costs	36	2	0.02
Packaging materials	163	10	0.08
Distribution and marketing costs	129	8	0.06
Total cost per litre	**1,560**	**100**	0.78
Processed milk market price	**2,000**		1
Value added	**440**		0.22

Source: Based on TAMPA, 2013.

The value added depends on the final use of the milk. Since in Tanzania most of the milk chilled by a BMC is sold fresh to neighbours or local informal markets, and is not processed, it is considered a lower value added of about TZS100 (or US$0.05) per litre. The BMC enables an additional 7 litres/day to enter the market, therefore, about US$128 (= 7 litres/day × US$0.05 × 365) are added in terms of value in a year due to the introduction of the technology (this added value is distributed among milk processors and transporters).

The SimGas technology supports the transformation of the smallholder dairy sector in Eastern Africa from quantity- to quality-based performance. The increased quality at the milk processor results in increased opportunities to process milk into higher value products, like cheese. The value would be higher if more milk was transformed into processed milk products that have a higher added value than fresh milk.[48]

Subsidies and taxes

SimGas benefits from the government programme to incentivize the use of domestic biogas systems in rural Tanzania. In 2015, through the Rural Energy Agency (REA) in cooperation with the Norwegian Embassy and the Netherlands government, a two-year subsidy scheme of over TZS9 billion (US$4.5 million) was approved (AllAfrica, 2016). The Tanzania Domestic Biogas Programme (TDBP) aims at building and running 10,000 biogas plants across the country in 2016 and 2017.

The first phase commenced in 2009 with over 12,000 biogas plants constructed, targeting more than 70,000 people. More than 60 digester construction enterprises were established and over 600 qualified masons trained (AllAfrica, 2016; DailyNews, 2016). Although SimGas is officially included under the TDBP subsidy scheme, which offered a discount of TZS240,000 (about US$120) to each plant developed through June 2015, to date the company has not received any subsidy (Pers. comm., June 2016).

48 Only about 180 million litres of marketed milk reach consumption markets in the form of processed products, but the country imports 60 percent of them (Ministry of Livestock and Fisheries Development Tanzania, 2015).

However, the subsidy has been included in the economic CBA as a cost for society, since it is paid with public money. Similarly, taxes represent positive flows from a societal point of view.

Tax revenue is received from the retail milk and dairy processing sectors. The biogas system is currently produced in Dar es Salaam. Some parts imported (cookstoves from China and gas seals from the Netherlands) encounter a 10 percent import duty (Ministry of Finance and Planning Tanzania, 2016). Tax revenues from import duty are about US$5/system sold, assuming a price of US$50 for the first gas seal imported from the Netherlands, and 10 percent of the value of a cookstove (US$1.5) and the milk chiller (US$60) every time they are replaced – if they are imported.

In 2012 the Tanzanian government introduced a zero VAT rate on milk and milk products (TAMPA, 2013). Thus, no milk tax revenues are accounted for in this analysis.

Assessment of environmental and socio-economic impacts

Soil quality

The digestate can be sold or used as organic fertilizer on the farmer's land. Effects vary according to the crop and soil type. In the financial CBA, the digestate is a co-benefit generating an additional revenue of US$408/household/year.

Farmers have to be made aware that the digestate has nutrient value, and its application can increase yields and substitute chemical fertilizers (Pers. comm. SimGas, 2016). Before the introduction of the biogas system, farmers may have applied the manure to the field directly to improve soil quality. However, the digestate has higher value.

SimGas has been investigating the positive effects of using digestate in a comparative study of applying digestate to crops vs. no digestate, resulting in a 25–200 percent crop yield increase when digestate was applied. This results in a conservative estimate of US$34/month or US$408/year, which is already included in the financial CBA. This income can be considered as the value of digestate or an opportunity cost for the increase in yield.

The co-benefits on soil quality in terms of soil organic carbon have not been quantitatively assessed.

Impact	Relevance
Positive	Moderate

Fertilizer use and efficiency

The organic fertilizer co-product can (i) replace chemical fertilizer use, (ii) increase the quantity or quality of the crops if no fertilizer was previously applied, or (iii) be sold. In Tanzania, the second option is the most likely situation as many farmers cannot afford to buy chemical fertilizers.[49] Therefore, the impact of the digestate use will be positive.

49 SimGas estimates that the value of the digestate produced by an average system is about US$300/household/year. This economic benefit was already internalized in the CBA.

Impact	Relevance
Positive	Moderate

Indoor air pollution

The use of biogas cookstoves reduces indoor air pollution and the risk of burns caused by the use of traditional biomass ovens or open fires (GIZ, 2017). This benefits the women who cook every day and the children who help or play nearby.

Costs of treating indoor air pollution and related diseases can be avoided; such costs are estimated to be about US$20–30/household/year (SimGas, 2016).[50] These can be included in the economic CBA as a benefit for society. It is mainly women who use the biogas cook stoves, so there are no changes in cooking responsibilities. However, biogas does introduce changes in cooking habits. In the benchmark scenario, women often cook on open fires, sitting on the floor. Biogas cookstoves are placed on a kitchen table, leading to an entirely different way of cooking, which can require time to adjust. Some women continue to cook on open fires next to the biogas stove because it fits better with cooking certain traditional dishes. SimGas therefore include cooking with biogas in customer training.

From the 6 m^3 digester system under analysis, around 1 m^3/day of biogas with an energy content of around 25 MJ is available for cooking. Detailed information on emissions of $PM_{2.5}$, PM_{10}, NO_X, SO_2, and other pollutants in mg or mg/ha have not been published by SimGas to date. The biogas cook-stove is a Tier 4 category for indoor emissions, whereas traditional biomass stoves are Tier 1 with around 60 percent more emissions (see Indicator Description above for more information on the Tier system).

Impact	Relevance
Positive	High

Water use and efficiency

A 6 m^3 digester system requires between 50 and 100 litres of water per day to mix with the manure. The quantity increases for bigger systems and depends on manure quality and other factors.

The water footprint of milk throughout the value chain is around 2.7 litres/day/litre of milk produced for the benchmark case, and around double that when using a biogas milk chiller (considering the milk water footprint plus the water required by the digester). On the other hand, assuming that around 93 percent of the total water input is at the feed production stage (FAO and USAID, 2015), the chiller reduces the water footprint by reducing milk spoilage and waste. Moreover, the milk chiller saves water when replacing the traditional milk cooling method of putting churns in cold water baths.

50 The mean annual spending on healthcare by Kenyan rural households is about US$50 (Chuma and Maina, 2012). The primary cause of death in both Kenya and Tanzania is from indoor air pollution (World Health Organization, 2011). Assuming health care costs in Tanzania are similar as in Kenya, about 50 percent of the total costs spent on healthcare (around US$20–30/year) are for treating indoor air pollution related diseases (SimGas, 2016).

The impacts on water use and efficiency are therefore very context-specific, particularly when the water is diverted from alternative uses or requires collection, which increases the workload of household members. While women are normally responsible for domestic water collection, calling on their children for support when required, men sometimes collect water for productive purposes including livestock watering. It is thus important to clearly identify the source of water for the biogas system (renewable or non-renewable, current water uses, etc.), to quantify the additional volume demanded, and to assess information on water collection (how will it be collected, by whom, how long will it take, etc.).

Impact	Relevance
Variable	High

Water quality

The biogas milk chiller does not directly affect water quality since water is not a co-product of the technology. However, use of the digestate may impact the N, P and K loadings and pH in the water nearby when synthetic fertilizer is used. Inappropriate application of both digestate and conventional fertilizers can contribute to water contamination and thus is very context-specific.

SimGas technicians provide customer training when installing the biogas digester at a farm. The training includes system usability, daily feeding scheme, digestate application, cookstove use, and milk chiller use. The training is given to the person responsible for operating the digester and at least one other household member.

The impact of the biogas system on the quality of water is assumed to be of low relevance, given the quantities and type of digestate produced.

Impact	Relevance
Variable	Low

Food loss

Milk deteriorates quickly at ambient temperatures in Tanzania, which is a major cause of production and post-harvest milk losses. Installing milk cooling devices enables farmers to reduce these losses. The BMC offers farmers the chance to market higher volumes of milk, but it cannot be assumed that all evening milk would have spoiled without the technology. In general, losses are in terms of missed sales and thus missed income for the dairy farmer, rather than in terms of spoilage (Pers. comm. SimGas, 2016).

The main goal from investing in a biogas milk chiller is to gain greater access to formal markets. If standards on milk cooling are not met, farmers cannot sell to formal markets. As a result of introducing the BMC technology, milk loss could be reduced by around 45 percent.

Impact	Relevance
Positive	High

Land requirement

The biogas milk chiller has minor impact on land requirement. The small areas required are usually non-agricultural land within the village.

Impact	Relevance
Negligible	–

GHG emissions

The technology reduces GHG emissions related to cooking and electricity generation systems (typically for the milk chiller), and mitigates GHG emissions by avoiding milk spoilage.

The replacement of solid biomass fuels results in carbon emission reductions of at least 6–8 tCO_2eq/year/system. An additional contribution to carbon emission reductions would come from avoiding deforestation and forest degradation. Around 23–24 percent of total fuelwood harvested in Tanzania is in fact considered non-renewable (Bailis et al., 2015).

If the biogas milk chiller replaces refrigeration systems powered by the national grid, around 40 kg of CO_2 emission would be avoided yearly. This is based on a demand of 100 kWh/year and a grid emission factor of 402 gCO_2/kWh.[51] If a milk chiller is run on fossil fuels, the GHG reduction would be even higher. For a regular 100 kWh/year refrigerator powered by a diesel-fuelled generator with a 30 percent performance efficiency and 3.36 kWh/litre diesel fuel, the diesel consumption is about 30 litres/year, equivalent to about 97 $kgCO_2$ emitted per year (assuming a GHG emission factor of 3.23 kg/litre (FAO, 2014b).

For this analysis, it is assumed that previous cooling technology does not exist. In this case, only the avoided milk spoilage due to the BMC contributes to GHG emission reductions, but these are very difficult to quantify. The agricultural emissions associated with the production of 1 litre of cow milk is around 6 $kgCO_2eq$/litre of milk (FAOSTAT, 2016). Assuming that spoiled milk is wasted, around 17 tCO_2eq would be avoided.[52] An additional GHG reduction can be associated with the use of digestate if it replaces synthetic fertilizers or soil amendments.

The only emissions that can be directly accounted for are those associated with the use of surplus biogas for cooking, ranging between 6–8 tCO_2eq/year.

Impact	Relevance
Positive	Moderate

Access to energy

From a gender perspective, individual households buy the biogas digesters. SimGas does not have a record of how many of them are women. In East Africa, it is usually

51 Average emissions factor for Tanzania grid from 2010-2012 (IEA statistics).

52 The spoiled milk not entering the market is considered a loss although it can be used locally, e.g. as animal feed.

the men that make the decision on household expenditures. However, it is often women who take care of the livestock and who express interest in buying a biogas digester. They are reported to have a significant influence on the purchase decision.

The biogas system allows the household to have access to relevant energy services, so the system can be classified as Tier 3: medium power appliances.

Impact	Relevance
Positive	High

Household income

At the household level, additional income from the BMC of US$2.48/day (about US$900/year) was calculated in the financial CBA. Tanzania's GDP per capita income (constant 2011 PPP dollars) in 2012 was US$1,654 (UNDP, 2014). From selling more milk on the market, the BMC can significantly impact household income, depending on numbers of people in the households and other factors.

The biogas cookstove reduces the health hazard from indoor pollution, consequently living conditions of the household are improved. A household can spend 25–40 percent of its income buying charcoal for cooking, which can be saved from using a biogas cookstove. The case study estimates conservative savings of US$250/household/year, but this can be up to three times more if the prices for fuelwood and/or charcoal rises.

If the benchmark situation uses a diesel generator to power cooling appliances, the farmer can save the money normally spent on the fuel, generating a co-benefit. However, for this analysis, it is assumed that previous cooling technology does not exist.

It is uncertain whether the men or women of the household sell the digestate and who then controls the income. Before sale, the digestate is dried in the sun, sifted to remove dirt, packed in bags, and sold to neighbouring farmers or at the local market. In the financial CBA, income from selling digestate amounts to US$408/household/year.

Impact	Relevance
Positive	High

Time savings

The BMC allows the milk to be stored overnight, therefore eliminating the need to spend time delivering the milk (usually to the neighbours) in the evening. Moreover, the biogas cookstove saves two to four hours a day of fuelwood collection, usually undertaken by women.

The dairy farmer (man or woman) transports the milk in churns of varying size by foot, bicycle or motorbike (depending on travel distance) to the milk collection centre twice a day. Alternatively, a worker is hired who has various jobs on the farm such as feeding cows, collecting manure, feeding the digester, fetching water, etc. The average time to travel from dairy farm to collection centre and back is 73 minutes.[53] For two deliveries, this takes about 2 hours, 43 minutes/day. If the evening milk can be cooled and kept cool overnight in the milk chiller, it can potentially be sold in the morning together with the morning milk, thereby saving 50 percent of the delivery time.

Depending on the context, the biogas system may require additional water that may need collecting, using buckets, a wheelbarrow, or a donkey.

Impact	Relevance
Variable	High

Employment

The introduction of the SimGas biogas system directly creates skilled jobs to manufacture, assemble, install, maintain, market, and sell the equipment. SimGas currently has 10 technical team members in Tanzania (including hub coordinator, customer service agent and research manager). The entire SimGas East Africa team (including SimGas Kenya) is about 80 people of whom 20 are women, including a country manager, 2 marketing managers, 5 hub managers, 2 customer-care managers, and 12 sales representatives. Technicians constitute about 70 percent of the workforce generated.

Moreover, the biogas milk chiller can indirectly generate employment since more milk production going into the market creates new jobs in transport, the MCCs and processing plants. A small team of technicians is estimated to be able to commercialize a large number of such systems (10 technicians can maintain about 6,000 systems). Since a trained technician costs about US$250–300/month (gross salary), the monetized co-benefit in terms of employment creation due to each milk chiller looks quite low (about US$6/year).

Impact	Relevance
Positive	Low

TABLE 4.12. Summary of environmental and socio-economic impacts (biogas-powered domestic milk chiller).

	Indicator	Impact
	Soil quality	Positive but not quantified
	Fertilizer use and efficiency	US$408/year
	Indoor air pollution	US$20–30/household/year
	Water use and efficiency	Variable
	Water quality	Variable
	Food loss	–45% (considered as benefit from milk selling)
	Land requirement	Negligible

53 According to market studies by SNV in Tanzania/Kenya/Zambia.

	GHG emissions	US$60/year 6–8t$CO_2$eq/year (however only 24% of woodfuel displaced is assumed non-renewable)
	Access to energy	From Tier 1 to Tier 3
	Household income	Impacts considered in the financial CBA
	Time saving	Variable (depends on the way household energy is supplied in the benchmark scenario)
	Employment	US$6/year

Note: green = positive impact, yellow = variable impact, red = negative impact.

Source: Authors.

Assessment of economic profitability

Economic profitability indicators of the BMC include taxes and subsidies, value added down the value chain, the impact of GHG emissions avoided, health related costs avoided due to indoor air pollution, and employment creation (Table 4.13.).

TABLE 4.13. Economic CBA of the case study (biogas-powered domestic milk chiller).

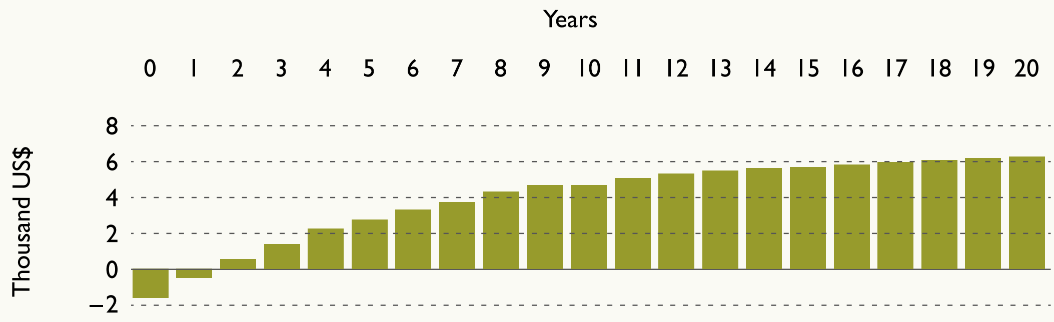
	Unit	Value	Notes
		Economic costs	
Subsidy for equipment	US$	120	Source: AllAfrica, 2016
		Economic Benefits	
Tax revenues from duty on technology import	US$	US$5D every 10 years, US$1.5 every 5 years	10% of imported equipment. Source: Ministry of Finance and Planning Tanzania (2016)
Value added along the value chain	US$/year	128	Authors' estimate
		Environmental and socio-economic impacts	
GHG emissions avoided	US$/year	60	Only 24% of fuelwood is considered non-renewable, therefore a net GHG saving of 1.68 tCO_2eq/year
Health related cost due to indoor air pollution	US$/year	25	US$20–30/household/year (SimGas estimate)
Employment creation	US$/year	6	10 technicians can maintain about 6,000 systems. A trained technician costs about US$250–300/month (gross salary)
		Economic profitability indicators	
NPV	US$	7,475	
IRR	%	92	

Note: A discount rate of 16 percent is assumed.

Source: Authors and sources as indicated in Notes column.

FIGURE 4.14. Cumulative discounted net economic benefits over 20 years (biogas-powered domestic milk chiller).

Source: FAO, 2016b.

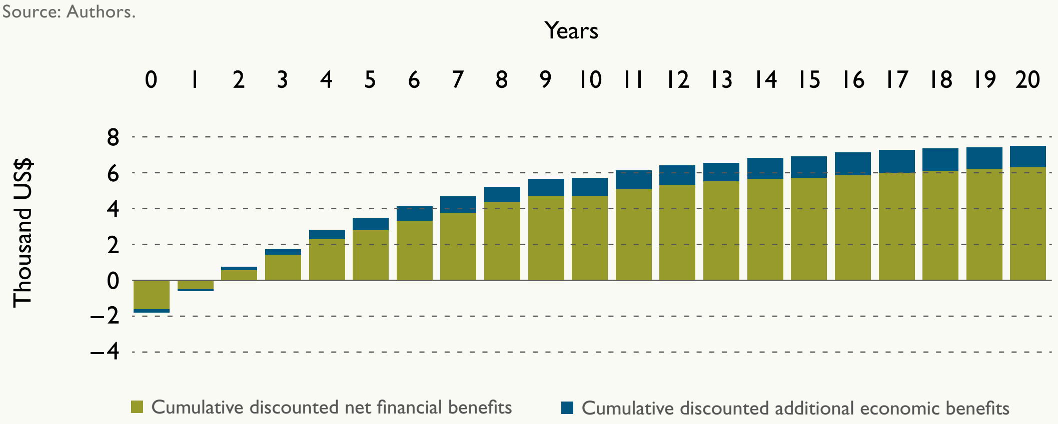


Results

The economic benefits from this biogas-powered domestic milk chiller are higher than the financial benefits, with the financial NPV being around US$1,200 lower than the economic NPV over a 20-year period.

FIGURE 4.15. Cumulative discounted net financial and economic benefits over 20 years (biogas-powered domestic milk chiller).

Source: Authors.

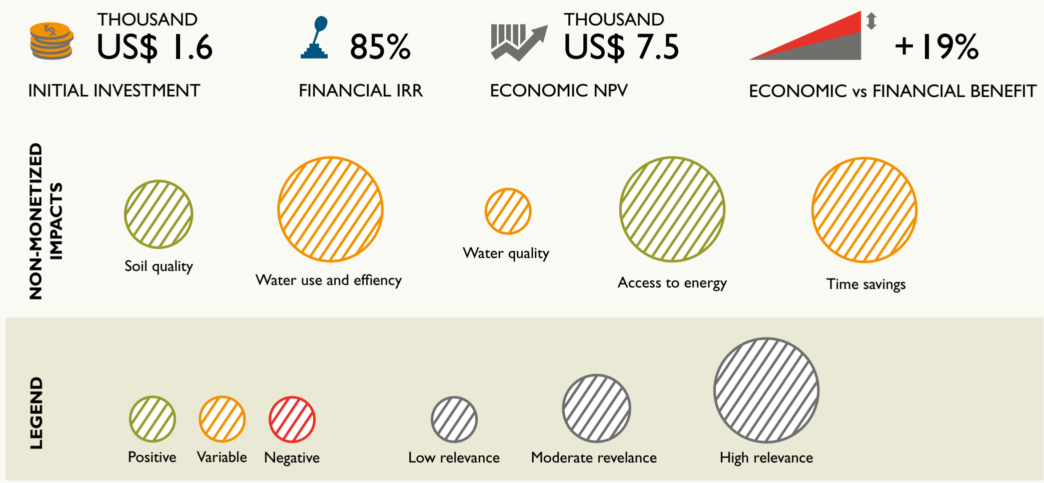


In addition to the economic benefits internalized in the analysis, the technology would bring additional (non-monetized) benefits in terms of improved soil quality and increased access to energy.

Conversely, depending on the specific location, the impacts on water use, efficiency and time saving can be negative. The impact on water quality can be negative if no appropriate disposal of biogas digestate is introduced.

FIGURE 4.16. Key figures of the case study (biogas-powered domestic milk chiller).

Source: Authors.



4.1.3. SOLAR MILK COOLER

When possible, the use of batteries should be avoided in solar cooling systems. The systems developed by the University Hohenheim/Germany for example uses ice as thermal storage.
Source: © GIZ/Alex Kamweru

Solar milk coolers (or small MCCs) powered by renewable energy allow operators to extend milk shelf life without using conventional, fossil fuel systems. Using solar energy for MCCs has been good practice for small businesses and communities for decades.

Both solar thermal and PV technologies harness the energy provided by solar radiation.[54] The efficiency in capturing solar energy is affected by many factors associated with the specific location, including local weather patterns through the year, dust and shading. Determining the right size of the solar energy system requires the skills and services of professionals well-versed in solar technologies.

In solar thermal systems, solar collectors (including flat plate, parabolic troughs,[55] Fresnel reflectors, or evacuated tube systems) use special surfaces which absorb sunlight and transform it into useful heat energy by heating up a fluid (such as oil). Evacuated tube collectors are particularly suitable for MCC operations since they are easy to install and low on maintenance requirements. The heat is transferred to the fluid flowing through the solar collector that carries it to a designated place where the heat is used, for example, to operate an engine to produce electricity.

Individual PV panels that generate electricity are composed of many solar cells connected to provide a capacity output of between 50 and 1,000 watts. Several panels can be assembled into a solar array. They produce an electrical direct current (DC) that can be converted to a single or three phase electrical alternating current (AC) using an inverter. Three basic types of PV cells – monocrystalline, polycrystalline, and thin film types – represent slightly different techno-economic characteristics. Polycrystalline cells are the most commonly used PV cells. Using solar PVs for MCCs makes most sense when grid connection is unavailable or unreliable. Solar PVs are usually coupled with an energy storage system.

Both solar thermal collectors and solar PV panels are only effective during daylight hours unless an energy storage system such as batteries, chemical storage, or ice banks is used. The surplus electricity not used during the day can be sold to the local power company if connected to a grid with feed-in capability.

When possible, the use of batteries should be avoided, since they are costly and inefficient means of storing electricity.[56] Batteries have a relatively short lifespan and are composed of materials potentially harmful to the environment. Lead acid or lithium-ion batteries are commonly used. The former is the cheaper solution but with a shorter lifetime, lower performance and higher risks for the environment (Buchmann, 2015).

The ultimate energy storage for solar MCCs however is a thermal ice bank (Figure 4.17). Ice bank tanks (IBTs) are cheap, reliable and environmentally friendly. Their cold storage capacity depends on size (and therefore cost), making them most suitable for small-scale applications.

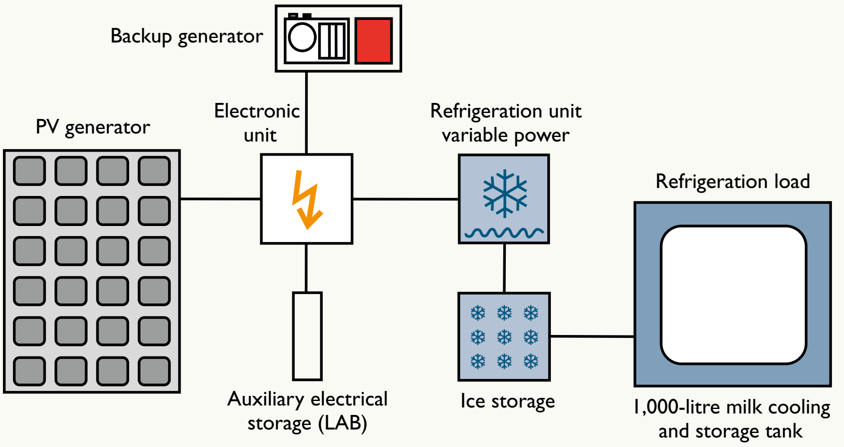
54 Data on global irradiation by location (W/m2) are publicly available from a number of sources such as http://pvcalc.org/global-irradiation-map (IRENA, 2016, European Commission, 2016b) or the ESMAP Global Solar Atlas, available at http://globalsolaratlas.info/.

55 A parabolic trough is a concave reflective body that converges solar radiation to a focal point, thereby concentrating solar radiation into heat energy. Heat energy can be used to drive a heat pump to generate electricity. Small-scale parabolic troughs use ammonia absorption system refrigeration technology to produce ice. A system to assist in milk cooling has been successfully developed in Kenya but has not been replicated throughout the region (FAO and USAID, 2015).

56 Considering the whole life of the investment, PV technology backed up with batteries may result in not being competitive, and hence are not investigated further. Other technological alternatives for household milk cooling include systems backed up by a thermal battery (see for example PROMETHEAN at http://modernfarmer.com/2014/02/chilling-cow/) or evaporative cooling systems (see for example THERMOGENN at http://www.smallholderfortunes.uga.edu/technology.html).

FIGURE 4.17. Solar PV cooling system with ice bank energy storage.

Source: FAO, 2016b.

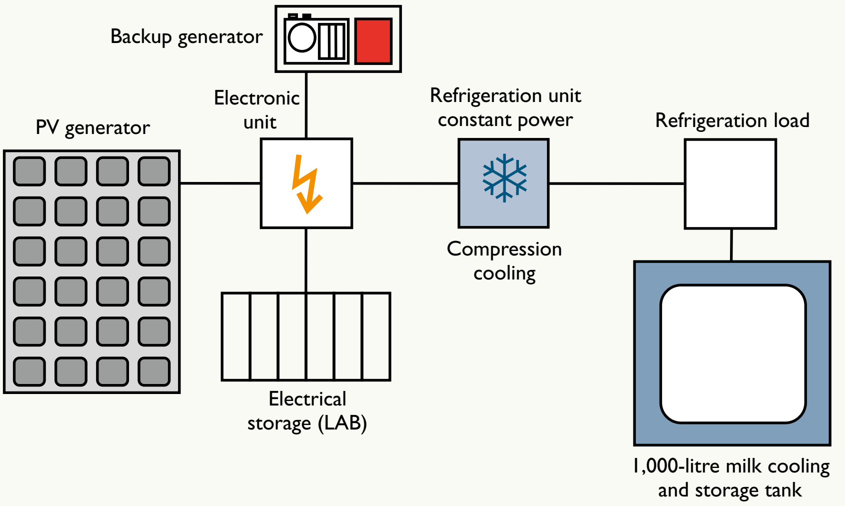


Combining PV and IBTs (European Commission, 2016a) requires further research to address the costs and benefits of economic activity on environmental and social dimensions (Grozdek, 2009), as well as research on thermal storage batteries (EVAPCO, 2009).

FIGURE 4.18. PV cooling system with electrical energy storage.

Note: LAB = lead acid battery.

Source: FAO, 2016b.



A number of additional technological solutions exist for MCCs, many of which are variations of those above.[57] In rural areas, solar MCCs can be bundled into stand-alone containers for the ease of delivery to remote areas and future relocation if necessary (Figure 4.19 and Figure 4.20).

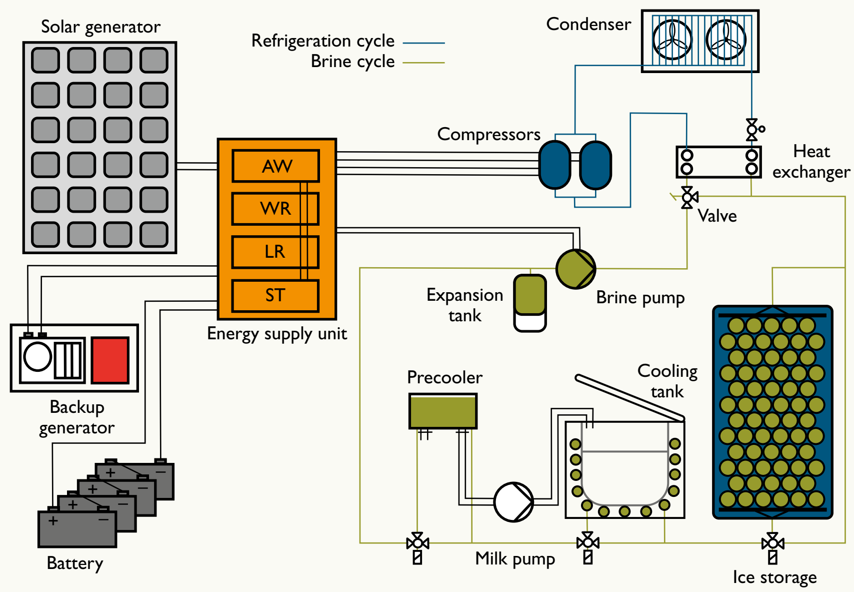
57 For more detailed and complete information about available technological solutions see FAO (2016b).

FIGURE 4.19. Mobile milk cooling centre using solar panels and ice bank.

Source: FAO, 2016b.

FIGURE 4.20. Stand-alone solar PV milk cooling unit with ice bank storage.

Source: FAO, 2016b.



COSTS

A conventional milk cooling system with a refrigerated direct expansion 500 litre milk cooling tank plus a backup generator set costs around US$8,500 including delivery and installation (FAO, 2016b). O&M costs (mainly for purchase of electricity or diesel fuel) and other business planning elements can influence the choice between conventional or renewable small-scale MCCs. Energy costs can vary widely depending on a multitude of factors (fuel type, price, ambient temperature, milk storage temperature, insulation of the system, subsidies, etc.). The avoidance of purchasing fossil fuel alone usually leads to an investment break-even point for stand-alone MCC systems relying exclusively on solar energy, despite their higher capital cost. Battery backup adds significantly to capital and O&M costs.

A 100 litre capacity milk cooling system consisting of a solar thermal collector (parabolic trough), an absorption chiller and a storage tank, costs around US$7,000, with an expected lifetime of at least 10 years and minimal maintenance and labour requirements for operation (FAO, 2016b).

The PV system can be 60–70 percent of the total equipment costs if the system is connected to the national grid with feed-in capability. Conversely, if energy storage such as batteries or IBT is required, the overall cost will rise considerably depending on the type of energy storage applied. In addition, a backup generator set may be required.

Solar milk coolers are more viable for small-scale off-grid applications, especially when combined with non-batteries power storage technology (such as ice banks, chemical storage, direct-driven refrigerators).

TABLE 4.14. Indicative system costs for cooling 500 litres of milk per day for systems with lead acid battery (LAB) and ice bank storage.

	Cooling system with LAB energy storage	Cooling system with ice bank energy storage
PV generator size	3.5 kW	5.5 kW
Energy storage	33.6 kW_{el}	45 kW_{th}
PV system & other equipment costs	US$13,700	US$31,570
Battery cost	US$10,000	US$2,600
Total system costs	US$23,700	US$33,170
Battery replacement after 4–5 years[a]	US$10,000	US$2,600
Distribution and marketing costs	129	8
Total costs	**US$33,700**	**US$36,770**

Note: [a]Depends on discharge rate and temperature of environment; el = energy stored in electrical form; th = energy stored in thermal form.

Source: FAO, 2016b.

MAIN IMPACTS

Where milk cooling facilities are not available, the main benefits linked to the introduction of solar MCCs come from the increased access to energy. In this case, MCCs can also provide further income due to the start of a new business and employment opportunities. If solar MCCs are an alternative to diesel-powered MCCs, they may improve incomes as the operator does not have to pay for fuel anymore (Milhoff, 2013).

Avoiding combustion of fossil fuel is another main benefit resulting in decreased GHG emissions in agro-processing. If milk conservation facility has not been available, solar MCCS also avoid food waste and extend the life of perishables – as do conventional milk cooling applications. However, solar MCCs are more capital intensive than conventional ones, so the payback is a risk, when the operator has to take a loan for installing a solar MCC.

Other risks of solar MCCs are of a technical nature, namely failures of the panels, generator, battery, or ice bank, which can cause major problems in locations where other milk cooling capacity is not available. A lack of locally available expertise in operating and maintaining the systems can further exacerbate these risks.

Larger milk cooling systems usually require three phase motors (ranging from 10 kW for a 2,000 litre cooling tank to 20 kW for 5,000 litres). Since this would require high investment costs in large arrays and energy storage units, solar is less suitable for large MCCs than for small-scale systems (FAO, 2016b).

Finally, water is required to clean the technology. This can lead to water pollution if there is no control over water discharge processes.

TABLE 4.15. Main advantages and disadvantages of solar milk coolers.

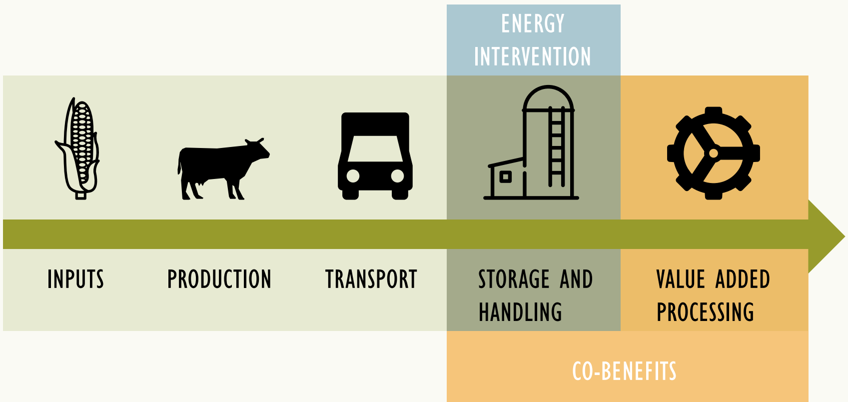
Advantages	Disadvantages
• Cold storage capacity becomes available for producers with or without unreliable grid power supply. The extended milk shelf life strengthens their market position and avoids premature milk spoiling. In some cases, a premium for better quality milk is paid by the market. • Income diversification (due to possible storage space rental) and decreasing dependency on expensive and polluting fossil fuels. • Creation of a new business in remote off-grid areas, contributing to (skilled) employment. • GHG emissions reduction.	• Energy storage is an issue that can be overcome by insulation, ice-banks or batteries. All these solutions need extra engineering and relatively high investment costs. • Solar cold storage systems are able to perform similarly to conventional systems but are more capital intensive. The higher investment can be offset in the long run by lower operating costs, but not always. • Water is required for cleaning.

Source: Authors.

CASE STUDY: SOLAR MILK COOLER IN KENYA

FIGURE 4.21. Location of the intervention and co-benefits of a solar milk cooler in the value chain.

Source: Authors.



In 2015, Nestlé commissioned the Sustainable Design Group (SDG) to produce two prototypes of the solar milk cooler for testing in Kenya.[58] Two solar-powered PV "MilkPod" demonstration units, each with a daily processing capacity of 600 litres of milk and costing around US$50,000, have been operating in Kenya for over two years. The Sustainable Design Group trained the users, and the systems are monitored. The milk cooling system and ice banks were manufactured by FullWood Packo,[59] a Belgian company with years of experience as a leading designer and manufacturer of milking systems worldwide. Packo also has manufacturing facilities in China. The solar energy system and the shipping container milk cooling centre were manufactured by the Sustainable Design Group in Gaithersburg, Maryland in the United States.

The MilkPod is self-contained and designed to be used by dairy conglomerates that collect milk in remote villages where electricity is either unreliable or unavailable. The target market is rural farms and dairies that do not have reliable electricity and rely on diesel generators.

This case study focuses on the two demonstration MilkPods installed in the Rift Valley Province of Kenya:

- at a "model dairy village"[60] of a cooperative farming system in Kabiyet; and
- in the Willens Dairy farm, near Eldoret where a small dairy farm of around 50 dairy cows produces close to 15,000 litres of milk per month.

58 Information reported in this section came from personal communication with John Spears and Mak Dehejia M. (2016) or was retrieved from the website of the company Sustainable Design Group (SDG, 2016).

59 More information is available at: http://www.packocooling.com/en/products/packo-milk-cooling.

60 See also: http://www.nestle-ea.com/en/media/pressreleases/Nestl%C3%A9establishinga%E2%80%98 modeldairyvillage%E2%80%99inKabiyetintheRiftValleyProvince.

Nestlé has given technical support to Kabiyet Dairies Co Ltd. since 2011. The purpose of the collaboration is to support Kabiyet improve their milk collection operation standards and support productivity improvement at farmer level. Kabiyet operates a standard Kenyan collection system, with affiliated dairy farmers of the cooperative supplying milk to any of the Kabiyet collection points. Kabiyet's role is to collect, bulk, cool, and market the milk on behalf of their farmer members. Three-quarters of the milk collection points have no cooling facilities.

The main limitation to installing more coolers is power availability from the grid; therefore, Nestlé proposed to the two dairy farms to try out the solar-powered MilkPod. Both farms operate in areas where power supply is unreliable. The PV-powered MilkPod appeared to be an attractive investment since the Rift Valley Province is predominantly sunny despite the wet season.

The technology providers are continually working to reduce the capital cost of the MilkPod while maintaining durability and reliability. For this reason, in this case study a lower capital cost of US$40,000 was assumed, paid at the beginning of the investment (hence a financing model was not included in the analysis).[61]

Feasibility analysis

In Kenya, most of the dairy farming is small-scale subsistence farming. Milk production is mainly from cattle, camels and goats. Dairy cattle produce about 70 percent of total national milk output (more than 3 billion litres) (FAO, 2011d).

Dairy farmers often produce milk for their own families as well as for daily income. In fact, many households have increased their milk production beyond what they can consume or sell to their neighbours. Typically, small farmers produce less than 5 litres/day of extra milk (Erickson, 2009) to sell to milk collection centres or the market. However, marketing milk to a more distant market is difficult as milk spoils within a few hours (Erickson, 2009).

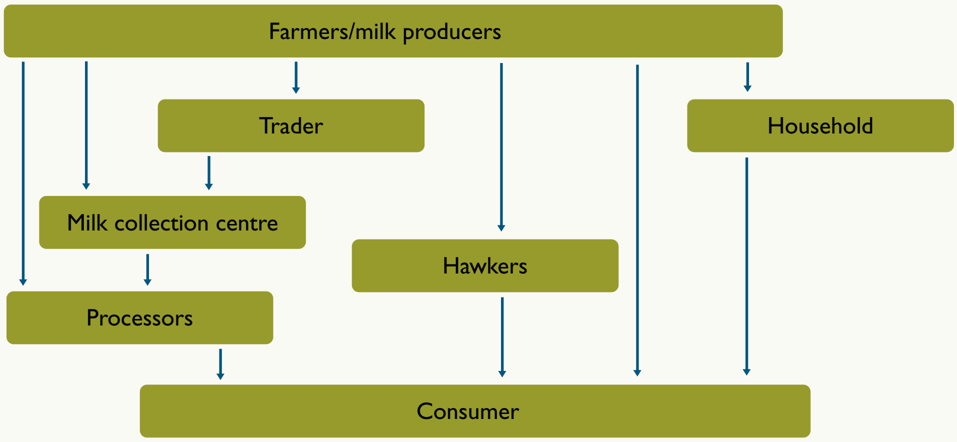
In most dairy producing areas in Kenya, milk collection is organized along collection routes, so individual farmers deliver the milk to the pick-up point or marketing agents collect the milk directly from the farms (Karanja, 2003). By joining farmer dairy cooperatives, smallholders have better access to rural milk collection facilities that cool the milk shortly after milking. Where an MCC is installed, the cooperative can collect from nearby members, chill and market the milk, and generate a revenue. Often the raw milk is collected from the MCC by one or more bulk buyers, who then divide and package it into commercially attractive quantities before selling it as fresh milk or to a dairy processor (Figure 4.22). With cooling facilities, farmers and cooperatives have more flexibility and do not need to rush the milk out to prospective customers.

61 Sustainable Design Group/Packo offers a reduced cost system without the shipping container for approximately US$3,000.

FIGURE 4.22. Milk flows in the value chain in Kenya.

Note: The actual value chain setup is highly dependent on the local context.

Source: Adapted from TAMPA, 2013.



The main challenges for the dairy sector are improvement of milk quality, access to the export market, reduction of wastage and reduction of costs along the value chain (FAO, 2011d). Collection systems enjoy economies of scale, which allow cost reductions and reduce economic risks for individual farmers. Cooperatives can offer input credit as well as other dairy-related services. When milk from different farmers is collected and mixed together, a major risk is the lack of hygiene standards, which can lead to the introduction of bacteria. To manage this risk effectively, timely cooling of the raw milk is essential, as much as ensuring hygienical handling and a reliable system for testing milk quality (TAMPA, 2013).

From an economic perspective, the initial investment in a relatively expensive milk cooler is a major issue in Kenya since access to credit can be difficult, even though similar investments elsewhere have shown a good return on investment within a few years (FAO, 2014b). A diesel-powered milk cooler also presents high capital costs and is strongly dependent on the variable cost of fuel.

From an institutional point of view, the energy (solar PV systems) regulations gazetted in Kenya on 28 September 2012 help ensure that all practitioners in the solar PV industry are professionals (ERC, 2014). No specific subsidies are available for the technology.

Description of the energy intervention

To comply with international standards, milk must be chilled to 4 °C within 4 hours of milking and stored at that temperature until it can be transported to the market. The MilkPod requires no grid power or generator and can chill and store 500–2,000 litres of milk on solar power alone. The system is a complete milk collection and chilling station including a milk receiving and testing section, a rapid milk chilling section and a milk storage section.

The Model S1 (Solar Powered Bulk Milk Chiller) is available either as modular components for installation in an existing facility, or as a pre-assembled milk chilling station in a shipping container (see Figure 4.23). It contains the following components:

- Milk cooling tank: open steel tank with a capacity of 600 litres or 1,200 litres with an internal curved finish that allows easy and thorough cleaning.
- Ice bank that cools milk 24/7 on demand, 50 percent faster than direct expansion (DX), and with a cooling capacity of 3–5 days without sun. The ice melts to chill the milk and keep it at a constant temperature until it is removed from storage. Running the chiller compressor only when the sun shines drastically reduces the required number of batteries and extends life of remaining batteries to over 10 years.
- Electronic controls, inverter, and batteries delivered fully assembled in a steel cabinet with lockable doors or in a sealed section of the shipping container. The inverter is covered by warranty. The management/control system signals problems.
- 6 kW_p solar PV panels is covered by warranty for 20 years and suitable for ground or roof mounting. In the case of a container, the solar panels are shipped inside, then mounted on the roof on site, so the container has to be orientated accordingly.
- Waste heat recovery unit: heat recovery from the compressor (using a plate heat exchanger) provides a source of heat that can be used to produce hot water to clean the system.
- Shipping container with insulated fibreglass roof panel walls and roof, urethane floor, LED lighting, stainless steel wash sink with hot and cold water connections, and a stainless steel table.

The system makes ice when the sun shines and stores the milk at a constant temperature, after both early morning and late afternoon milkings. It can cool 250 litres of milk from 41 °C to 10 °C in 30 minutes, and bring it down to 4 °C in 1 hour.

FIGURE 4.23. SDG solar-powered bulk milk cooler.

Source: SDG, 2016

Financial CBA

Benchmark scenario

The costs and benefits for a collective farmer cooperative investing in a MilkPod were compared with a benchmark cooling system of a 10 kW diesel generator and a 600 litre (direct expansion, DX) milk cooler. The cost of this base system can vary depending on the country and quality of the equipment. Socio-environmental costs of manufacturing either cooler type were excluded, but socio-environmental benefits and costs throughout the milk value chain were accounted for. The costs for the benchmark system are dependent on the price of fuel, the efficiency of the generator to convert diesel to electricity, and the capital cost of the generator.

In Kenya, a standard 1,000 litre milk cooler costs around US$7,000 (FAO, 2014b), with an associated 10 percent two-year micro-credit interest rate, and electricity cost from the grid of US$0.01/litre of milk per day. In case of an unreliable electricity supply, the purchase of a generator and its fuel costs should be added to the costs. The main benefit of cooling is the possibility to sell more milk at US$0.30/litre (FAOSTAT, 2016). According to FAO (2014b), a standard milk cooler would save 150 litres of milk per day for each 1,000 litres milk cooled (i.e. 54,750 litres/year). The investment breakeven point is reached after two years.

The whole benchmark system (milk cooler and equipment, generator, three phase motors, washing equipment, and water heater) has a capital cost of US$10,500, with the replacement of generator and milk cooler equipment every 8 years for a cost around US$8,500.

The temperature of the milk upon its arrival at the MCC depends on the temperature to which it was exposed during transportation. In a small-scale MCC, electricity consumption for refrigeration is about 120–145 MJ/1,000 litres of milk. The electricity is needed to remove heat (using ice bank or direct expansion refrigeration systems) and stir the milk. In addition, approximately 25 MJ of thermal energy per 1,000 litres was added for washing the equipment. Water consumption may reach 300 litres/1,000 litres of milk in these types of plants (FAO, 1992b).

Since diesel is also used in small-scale thermal electricity generation and for water heating, diesel consumption is about 8.5 litres/day (assuming an engine efficiency of 30 percent). The price of diesel was KES80/litre (US$0.80/litre)[62] corresponding to an annual fuel cost of about US$2,500.

The following assumptions were made in the CBA:

- **Interest rate:** An interest rate of 11 percent was selected based on the 11 percent interest rate of 9-year Kenyan government bonds; commercial lending rate of 17.9 percent; the Central Bank of Kenya's official interest rate of 11.5 percent and the deposit interest rate of 7.285 percent.[63]

62 In Kenya, in June 2016 the price of diesel varied from KES70.4/litre in Mombasa to KES87.5/litre in Mandela. In December 2015, a maximum allowed diesel price was set to KES78.5/litre (ERC, 2016).

63 Data from the Central Bank of Kenya statistics (https://www.centralbank.go.ke) retrieved online June 2016.

- **Life expectancy of the technology:** The expected life of the cooling tank, ice bank, PV panels, water heater, waste heat recovery unit and the other steel applications in the container is more than 20 years. Generally, little maintenance should be required. However, batteries will have to be replaced every 10 years for about US$3,000.

- **Scale:** The shipping container is 6.1 m long, 2.44 m high and 2.44 m wide. The ice bank capacity can cool 2,500 litres of milk without additional energy input, and therefore can go several days without sunshine. The solar panels can fully charge the ice bank in one sunny day under Kenyan levels of irradiance. The operating time of the compressor depends on many variables, in particular on solar irradiation. In sunny weather, a few hours of operation are sufficient to create the ice. The system is designed for about 1,200 litres of milk per day, one-half in the morning and the other one-half in the evening. The ice water can chill and maintain milk at 4 °C for 3 to 5 days without solar input.

Costs

Capital cost: SGD aims to commercialize a 600 litre system for US$40,000.[64] This would include a cooling unit and ice bank (US$15,200); a 6 kW solar PV system, a rack, four batteries, inverters, and controls (US$19,290); and the shipping container with insulated walls and roof, LED lighting, stainless steel wash sink with hot and cold water connections, water heater, and a stainless steel table (US$5,510). The additional cost compared with the benchmark system is for the solar power system and ice bank.

In the solar MilkPod, heat is recovered by providing hot water, hence providing additional savings on energy costs.

The two demonstration MilkPods were shipped and installed by SDG and PACKO technicians, who also trained the operators from the village cooperatives. The expected life of the cooling tank, ice bank, PV panels, water heater, waste heat recovery unit and the other steel applications in the container is more than 20 years.

Maintenance and replacement costs: SDG designed and built the prototype solar milk chiller and milk tanks. Packo built the ice bank, since this company has a big network of distributors that can maintain and repair the systems, though little maintenance should be required. It was assumed the batteries will be replaced every 10 years for about US$3,000 and will be available through Packo's worldwide distribution network (also the inverter is available through Packo's network).

Routine maintenance includes washing the tank once per day and washing the solar panels when dirty, taking about 2 hours, 6 times/year.

Operating cost: Inputs are labour and water to wash the milk tank, and 50–150 litres of water per day for the open tank milk chiller (for 365 days/year). The ice bank does not consume water as it is recycled, though a small amount may be lost by evaporation. Since the benchmark system would need to be washed as well as the solar MilkPod, no additional water requirement was accounted for in the financial CBA.

64 Costs are determined by the local market. For example, in India milk tanks are very cheap but of poor quality compared to the Packo tanks, so quality and regional costs need to be considered.

The MilkPods operate automatically, but it was assumed that a full-time worker is required to fill the tank after the two daily milkings, clean it, and turn on and monitor the system. The diesel generator in the benchmark system was assumed to require a similar amount of time for ordinary maintenance.

The minimum consolidated wage for general workers in rural areas in Kenya of KES54.70 (US$0.55) per hour (WageIndicator.org, 2016) was used to monetize labour costs.

Compared to the benchmark scenario, energy is saved since water is heated with waste heat from the compressor system.

No cost for land rental was included in the analysis.

Benefits

Energy saving: The main benefit from adopting the solar MilkPod is costs avoided from repair, maintenance and fuel compared with the diesel generator benchmark. The avoided cost of fuel is accounted for as a negative cost (benefit) of the MilkPod.

It was assumed that about 8.5 litres of diesel are consumed every day to cool 600 litres of milk fresh and to produce thermal energy for heating water to clean the system. Therefore, the MilkPod saves almost 3,000 litres/year which at US$0.8/litre totals about US$2,500.

Milk quality and quantity: An ice bank can cool milk to 4 °C in less than 1 hour whereas conventional DX chillers can take up to 3–4 hours. The quality of the milk is therefore improved by reducing bacteria growth and the selling value is increased (Pers. comm. SDG, 2016). When the milk is collected from numerous small farmers, it can take up to several hours to reach the MilkPod. With a high ambient temperature, the milk deteriorates quickly and therefore can be rejected at a quality check due to bacteria growth. Rejections are higher during the wet season, when production is high and roads are in poor condition. By cooling the milk faster and increasing its quality, the MilkPod can reduce rejection and therefore losses. Precise data on the quantity that can be saved by cooling the milk faster is unavailable, so it is assumed the cooperative will save about 5 percent of the milk, equivalent to 30 litres/day.

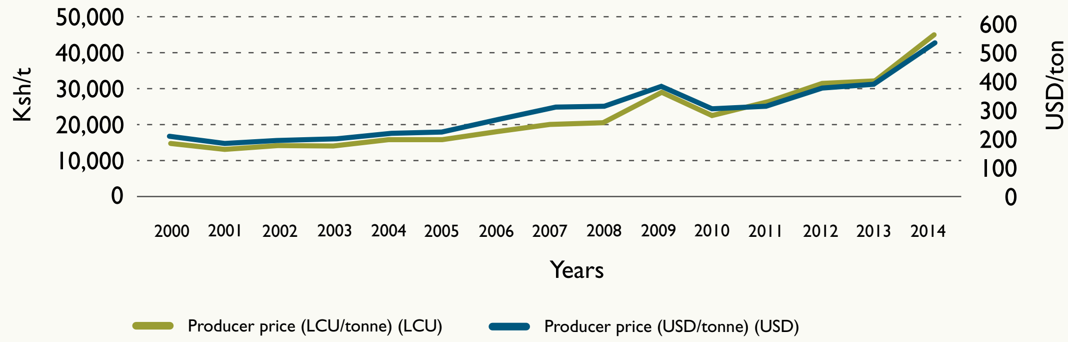
For the cooperative, one option is to sell milk to the major dairy processors, which pay a producer price of about KES30–40/litre. The retail price of milk after processing and packaging is about KES60/litre (Pers. comm, Willens Dairy Farm, 2017).[65] Therefore, the cooperative would benefit if its milk could directly reach the consumer, although additional costs occur in transport, distribution, packaging, and selling. Moreover, in the urban milk market there is competition from large dairy companies.

Milk price: The price of milk has risen in recent years and significantly influences the revenue from the milk cooler (Figure 4.24). Policies have been put in place to reduce the milk price hike of 2014.

65 Information collected in an interview with the farm owners in February 2017.

FIGURE 4.24. Whole fresh cow milk producer price in Kenya from 2000–2014.

Source: FAOSTAT, accessed 5 July 2016.



The price of the milk paid by the dairy processor or creamery is assumed to be KES30–40/litre depending on the quantity sold and the season, whereas the retail price for milk is KES60/litre (Pers. comm., Willens Dairy Farm, 2017). The cost of transportation from the farm to the cooling unit is about KES1-2/litre. The milk production costs at farm level are around KES25/litre, therefore the revenues at dairy cooperative level for each litre of milk are around KES8 (US$0.08). Therefore, saving 5 percent of the milk collected results in an additional revenue of US$876/year.

The main costs for dairy farmers are for fodder and general animal husbandry. The feed/forage used by farmers includes maize stover, poultry waste (dried), hay, silage, locally available grains, and grazing (most common feed source). The dairy feeds available on the market are low quality and expensive (FAO, 2011d). It was assumed the milk price will be constant over the 20-year period since the increasing trend in price (up by 9 percent in the period 2000–2014) is counter-balanced by inflation. Still, it must be taken into account that price volatility is high, with price elasticity changes among income groups (FAO, 2011d).

Financial profitability

Assuming an interest rate of 11 percent, the financial NPV of the solar milk cooler compared to the benchmark diesel generator and DX milk cooler over a horizon of 20 years is US$1,501 with a 12 percent IRR (Table 4.16).

TABLE 4.16. Financial CBA of the solar milk cooler compared with the benchmark of a diesel generator with DX milk chiller.

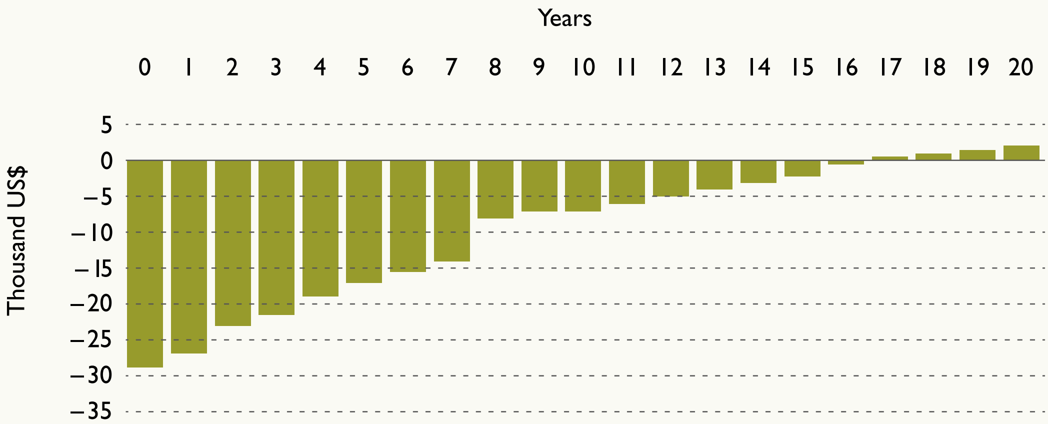
	Unit	Solar MilkPod with ice bank	Diesel generator & DX milk cooler	Notes
Life expectancy technology	year	20	8	
		Financial costs		
Capital cost	US$	40,000	10,500	Pers. comm. SDG
Replacement cost	US$	Battery replacement at US$ 3,000 every 10 years	Generator replacement at US$ 8,500 every 8 years	Pers. comm. SDG
Operating costs	US$/year	1,405	3,891	
Energy costs	US$/year	0	2,486	Diesel price: US$0.80/litre. (2,613 + 494) × 0.8 = 2,486
For milk cooling	litre of diesel/year	0	2,613	
For water heating	litre of diesel/year	0	494	
Labour cost	US$/year	1,405	1,405	Wage: US$0.55/h
Land cost (rent)	US$/year	0	0	
		Financial benefits		
Milk revenues	US$/year	17,520	16,644	Assuming the solar milk cooler loses 5 percent less milk by cooling milk faster (17,530 = 16,644 + 876)
		Financial profitability indicators		
NPV	US$	1,501		
IRR	%	12		

Note: The following assumptions were made: US$1 = KES100; discount rate of 11 percent.

Source: Authors and sources as indicated in Notes column.

FIGURE 4.25. Cumulative discounted net financial benefit over 20 years (solar powered milk cooler).

Source: Authors.



The price of milk and diesel, the exchange rate, the discount rate, and the profitability indicators can change significantly. For instance, the exchange rate influences the price at which the technology is imported, so a depreciation of the Kenyan Shilling can greatly increase the cost of the MilkPod, and reduce the NPV of the investment. The discount rate determines the actual value of future discounted flows. If the discount rate increases, less value is given to future flows.

The **price of milk** is key to determining the benefits of the technology. For instance, introducing a price premium for milk of better quality would increase milk revenues for cooled milk. This would increase the NPV of the solar milk cooler.

A linearly increasing **diesel price** of 10 percent/year increases the operating costs of the benchmark case, so the NPV and IRR of investing in the MilkPod would rise (NPV = US$2,886; IRR = 12 percent).

These variations confirm that it is important to select reasonable parameters for the analysis and to take into account key variables over the lifespan of the investment.

Economic CBA

Value added along the value chain

In 2004 a reform was introduced to incorporate small-scale milk producers and traders into the milk value chain. Today, nearly 800,000 smallholders depend on dairy for their livelihoods. The dairy sector provides employment to over 350,000 people in milk collection, transportation, processing, and sales (Karaimu, 2010).

In rural areas at the household level, women usually take care of the cows and the milking. Surplus milk goes to brokers or hawkers who take the milk to neighbours, cooperatives, or processors early in the morning. The price obtained by the producer varies significantly depending on to whom the milk is sold. The dairy cooperative was assumed to sell the cooled milk at US$0.35/litre to a dairy processor (about KES35/litre). After the introduction of the solar MilkPod, the cooperative reduced the milk rejection due to better quality of their milk. Therefore, the financial analysis incorporates an additional revenue for the MCC owner of US$876/year (for details see aboe).

The Sustainable Design Group estimated that the local production of better quality milk can meet the growing demand for milk products in the region, and thus has a strong economic development potential. Farmers get more money for their milk so they may increase their production, increasing local economic activity. Compared to the situation with no milk cooling facilities, the Kabiyet Dairies Co Ltd., and Kormaet Milk Collection Centre managed to significantly increase the volume of milk collected.[66] However, this increase was not exclusively correlated to the introduction of the solar MilkPod, hence it was not considered in the analysis.

66 Milk collection was started in May 2015, with volumes prior to that date below 300 litres/day, all from the morning milking. By June 2015, collection was 475 litres/day (90 percent from the morning milking), and by October 2015, collection exceeded 1,150 litres/day (75 percent in the morning).

In this case study, the value added for each litre of milk is considered to be around US$0.20/litre. In fact, the cooperative can sell the cooled milk to a trader, a processor, or directly at the market for US$0.60/litre. The value added is equal to the difference between the cost of collecting, transporting, cooling, and packaging the milk (about KES0.40/litre) and its final sale price (KES0.60/litre). By saving about 30 litres of milk per day from rejection and spoilage, the solar milk cooler generates a value added along the value chain of about US$2,190/year, which is incorporated in the economic CBA. This potential value added is spread between dairy farmers, transport, MCC, and other agents down the value chain.

Subsidies and taxes

SDG received some grants from the state of Maryland but the solar milk chiller has been privately funded to date (Pers. comm. SDG, 2016). Many governments have solar subsidies that could apply, but in Kenya the solar milk cooler does not benefit from any subsidies or incentives.

Solar-powered equipment and accessories (including deep cycle sealed batteries that exclusively use and/or store solar power) are exempt from import duty.[67] Hence, the Kenya Revenue Authority did not impose duty on the imported MilkPods.

A tax of KES 40/litre of diesel is used for the analysis (The Star, 2016). Therefore, with the adoption of a solar milk cooler, the government loses US$1,243/year of revenue from taxation of the diesel used to power a standard (direct expansion) milk cooler.

Assessment of environmental and socio-economic impacts

Soil quality

Impact	Relevance
No impact	–

Fertilizer use and efficiency

Impact	Relevance
Negligible	–

Indoor air pollution

The introduction of a solar milk cooler instead of a diesel-powered system can significantly reduce air pollution in the community, but not indoors. Noise and health-related issues linked to the use of a diesel generator are reported as the primary drivers to pursuing renewable alternatives (Pers. comm. SDG, 2016).

Impact	Relevance
No impact	–

67 See http://www.revenue.go.ke/customs/pdf/Fifth_Schedule_Exemptions.pdf.

Water use and efficiency

About 100 litres of water per day is used to clean the system both in the benchmark and in the MilkPod case. The impact on water use and efficiency depends on the source of water, how it is collected, by whom and how long it takes. However, since the issues are the same in both cases they are not considered further.

Impact	Relevance
Variable	Moderate

Water quality

The MilkPod can have a positive impact on water quality, since the benchmark diesel generator could have contributed to water pollution. On the other hand, the wastewater from cleaning has to be properly discharged, if a detergent is used, to avoid impacting on local water and soil quality.

In Kenya, the establishment of milk coolers and processing plants must conform to the Environmental Management and Coordination Act (1999), the Waste Management Regulations (2006) and other regulations such as those for water quality (FAO, 2011d). The temperature and pH change of the water used to clean the system should be assessed, especially when a detergent is used. However, this impact can be considered of low relevance.

Impact	Relevance
Variable	Low

Food loss

Rejection of spoiled milk is a result of poor handling and the time taken to reach markets. In the financial CBA, it is assumed that, by cooling the milk faster than a standard diesel generator, the solar milk cooler reduces spoilage and rejection at the processing stage by 5 percent. This assumption is justified by the fact that the milk can take up to several hours to reach the cooling unit, therefore a rapid cooler significantly increases its quality and reduce spoilage. An increase in quality results in fewer rejections at the market or processing stage. The overall added value of this avoided milk loss amounts to about US$3,000/year (US$876/year at the farmer/cooperative level and US$2,190/year down the value chain).

Impact	Relevance
Positive	High

Land requirement

No significant impact. The system does not require extra space if compared to conventional milk coolers as PV panels are usually installed on top of the container.

Impact	Relevance
No impact	–

GHG emissions

Using a generator to power the 1,000 litre milk cooler generates about 15 $MtCO_2eq$/year. For a milk chiller powered by diesel generator, the total GHG emission (direct + indirect) factor is 3.241 kg CO_2/litre of milk or 0.973 kg CO_2/kWh (FAO, 2014b). For the solar 600 litre MilkPod, this is equivalent to a savings of about 10 $MtCO_2eq$/year. Assuming a social cost of carbon of US$36/tonne this is equivalent to US$360/year.

Impact	Relevance
Positive	High

Access to energy

The MilkPod replaces conventional electricity-powered MCCs and may enable access to milk cooling where it is not available due to logistical constraints. In a solar-powered MilkPod, no extra thermal energy is required to heat the water for cleaning the system. Since the electricity generated by the PV is used only to power the MilkPod, the technology has no spillover impacts on access to modern energy services as described in the indicator: Tier 0.

From a social point of view, the MilkPod can empower the community's money from a diesel generator flows out of the community, all revenue from the MilkPod stays within whereas – if the MilkPod is owned and financed by the community – and can generate development.

Impact	Relevance
Negligible	–

Household income

The main impact on income is in terms of savings from the money spent on a diesel generator. With the MilkPod there is no diesel fuel cost (saving about US$2,496/year) and no engine maintenance cost (which requires replacement for US$8,500 every 7.5 years). Also, there is no variability in income due to changes in fuel prices over time. Moreover, the solar technology allows increased revenue due to less milk spoilage and rejection (US$876/year). Both these impacts were accounted for in the financial CBA.

The extent to which increased revenue affects gender equality depends on women's access to the dairy cooperatives that manage the MilkPod. Women need to be motivated to become members of the dairy cooperatives so they too can benefit from the cooperative incremental income resulting from the investment. Where men typically comprise all or most members of dairy cooperatives, they stand to benefit disproportionately more than women who may be restricted to the production node of the value chain.

Impact	Relevance
Positive	High

Time savings

There is no important change to the time spent performing unpaid activities after the intervention.

Impact	Relevance
No impact	–

Employment

In Kenya, at the farm level, for every 1,000 litres of milk produced daily, dairy activities generate an estimated 23 full-time jobs for the self-employed, 50 permanent full-time jobs for employees, and 3 full-time casual labour jobs, making a total of 77 direct farm jobs (FAO, 2011d). The dairy processing sector provides 13 jobs (12 direct and one indirect) for every 1,000 litres of milk handled daily. In the informal sector, it is estimated that about 18 employment opportunities are created for every 1,000 litres of milk a day handled through this channel (FAO, 2011d).

In this case study, no technical agents were directly employed in Kenya as a consequence of the introduction of the MilkPod technology. This energy intervention can however have a potential positive indirect impact since it requires the development of new supporting services.

Since the impact is negligible in our case, the impact was not covered nor monetized.

Impact	Relevance
Negligible	–

TABLE 4.17. Summary of environmental and socio-economic impacts (solar powered milk cooler).

	Indicator	Impact
	Soil quality	No impact
	Fertilizer use and efficiency	No impact
	Indoor air pollution	No impact
	Water use and efficiency	Variable
	Water quality	Variable
	Food loss	US$3,066/year (considered in the financial CBA and in the value added)
	Land requirement	No impact
	GHG emissions	US$360/year (10 $MtCO_2eq$/year)
	Access to energy	No impact
	Household income	US$2,496 + US$876/year (considered in the financial CBA)
	Time saving	No impact
	Employment	Negligible

Note: green = positive impact, yellow = variable impact, red = negative impact.

Source: Authors.

Assessment of economic profitability

The main economic impact of the solar milk cooler is in terms of value added along the value chain, due to the reduced milk waste at farmer/cooperative level, which affects the quantity of milk down the value chain. On the other hand, the solar milk cooler reduces government revenue from the tax on diesel (Table 4.18). The main environmental and socio-economic benefits are in terms of GHG emissions avoided and food loss reduction. However, the benefits in terms of food loss reduction are already accounted in the financial CBA (as cooperative revenues) and as value added along the value chain. Hence, they are not counted again. The economic NPV of the investment is much more positive than the financial one and reaches US$11,911 with a 17 percent IRR.

TABLE 4.18. Economic CBA of the case study (solar powered milk cooler).

	Unit	Solar MilkPod with ice bank	Diesel generator & DX milk cooler	Notes
		Economic costs and benefits		
Value added along the value chain	US$/year	2,190	0	Assuming US$0.20/litre of milk
Tax revenue from diesel use	US$/year	0	1,243	Assuming a tax of US$0.40/litre of diesel
		Environmental and socio-economic benefits		
GHG emissions avoided	US$/year	360	0	10 $MtCO_2eq$/year at US$36/tonne
		Economic profitability indicators		
NPV	US$	11,911		
IRR	%	17		

Note: The following assumptions were made: US$1 = KES100; discount rate of 11 percent; wage for the operator of US$0.55/hour; final price of diesel of US$0.80/litre.

Source: Authors.

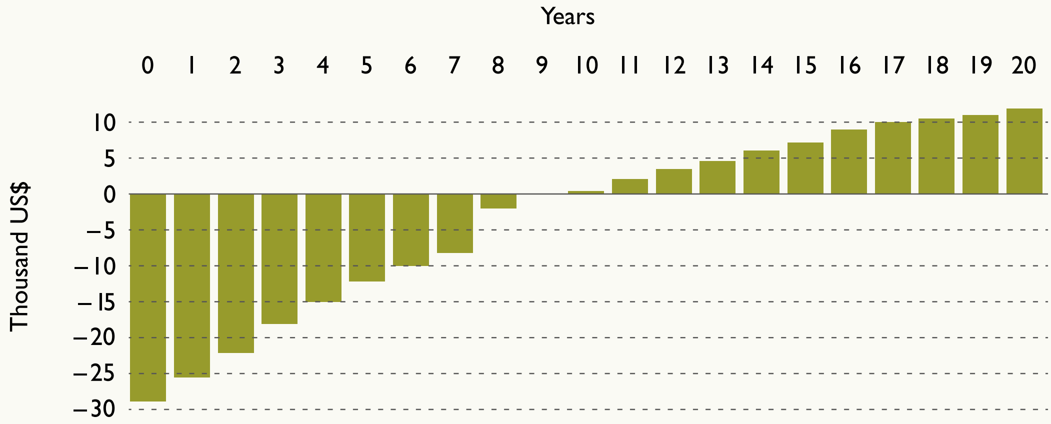
Results

The financial CBA of the solar MilkPod assumed a DX milk chiller powered by a diesel generator as benchmark. The relatively high capital cost of the solar technology implies a financial payback time of about 17 years. Financial mechanisms to spread the initial cost of the technology would result in a shorter payback time and higher NPV and IRR. An increase in key parameters such as price of milk, price of diesel, or interest rate could drastically change the picture, increasing the benefits of the technology.

The analysis of this case study also highlighted the benefits of the technology in terms of avoided milk losses that generate a positive financial benefit and add value along the value chain. Faster cooling would in fact result in reduced spoilage and higher quality milk, limiting rejection at the market/dairy processor.

FIGURE 4.26. Cumulative discounted net economic benefits over 20 years (solar powered milk cooler).

Source: Authors.



Moreover, the technology has a positive impact on GHG emission reductions, monetized in the economic CBA. Conversely, negative impacts could result from poor disposal of the wastewater, also impacts on gender equality could be negative. It is possible that targeted activities are required to ensure that women benefit (at least) equally from the MilkPod – principally through membership in dairy cooperatives but also through equal access to new employment opportunities.

FIGURE 4.27. Cumulative discounted net financial and economic benefits over 20 years (solar powered milk cooler).

Source: Authors.

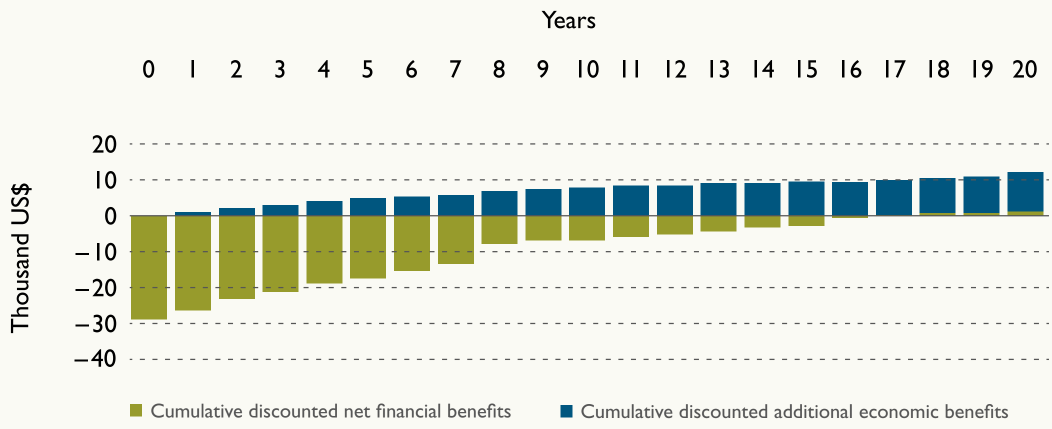
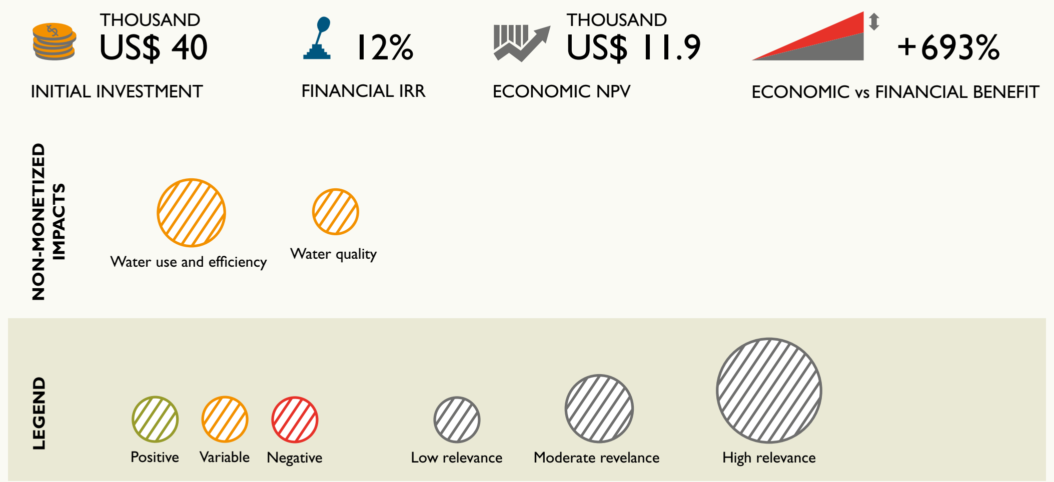


FIGURE 4.28. Key figures of the case study (solar powered milk cooler).

Source: Authors.



4.2. VEGETABLE VALUE CHAIN

Source: © GIZ/Folke Kayser

4.2.1. SOLAR COLD STORAGE

Solar cold storages expand harvested fruits' and vegetables' shelf life without depending on fossil fuel.
Source: © Sustainable Design Group/John Spears

Cold storage of harvested vegetables using solar power allows operators to extend vegetable shelf life without depending on fossil fuel-powered equipment that releases GHG emissions. Solar cool stores can reduce food losses in remote areas where no grid-power is available. Benefits include potential income increases from vegetable sales; decrease of energy costs for conventional cold storage; and access to reliable energy where grid electricity is unreliable. Depending on the specific technology and the existing situation, Solar cool stores can also offer competitive installation and O&M costs. In order to select the optimal solar cooling technology for a specific location, the product type, producer type, energy demand, capital cost, and technology intensity need to be considered.

To assess the efficiency of the cooling process, where detailed data inputs and ambient environment details are unknown, the Q_{10} quotient[68] can be used as rule of thumb (Table 4.19): for every 10 °C decrease (first column) of storage temperature (to reach the target temperature), the shelf life of the perishable product increases two to threefold (fourth column).

68 Q_{10} is a quotient between two rates of deterioration temperatures that differ in 10 °C (hence, it has no units). The relative velocity of deterioration (third column) means that if 0 °C has a value of 1, the relative velocity of 10 °C has a value of 3 (multiplying by Q_{10}). The fourth column is the relative amount of time of the product's post-harvest life, in this case 0C corresponds to a value of 100. The rest is obtained by dividing by the relative velocity values in column three. The daily loss is also calculated as a percentage (dividing 100 by the relative post-harvest life column).

$$Q_{10} = \frac{\text{Rate of deterioration at temperature T + 10 °C}}{\text{Rate of deterioration at T}}$$

TABLE 4.19. Effect of stored temperature on deterioration rate of non-chilled fresh vegetables and days of postharvest life.

Temperature	Relative velocity of deterioration (reference value of 1 for T = 0 °C)	Relative postharvest-life (reference value of 100 for T = 0 °C)	Loss per day (%)
0 °C	1	100	1
10 °C	3	33	3
20 °C	7.5	13	8
30 °C	15	7	14
40 °C	22.5	4	25

Source: FAO, 2004.

The cold storage properties of vegetables are important factors when selecting the most appropriate cold storage technology. Bunched carrots and leafy vegetables mostly require a storage temperature close to 0 °C with high relative humidity, separation from fruits and fruit-like vegetables like tomatoes that produce ethylene through respiration, and possibly hydro-cooling. The optimal storage condition for green beans is higher but below 8 °C, while ripe tomatoes should be stored between 10–21 °C (Table 4.20).

TABLE 4.20. Optimal storage temperature for primary vegetables.

Vegetable	Shelf life at 35 °C ambient temperature (days)	Optimal storage temperature (°C)	Shelf life under optimal storage conditions (days)	
			Minimum	Maximum
Low temperature, moist storage				
Carrots (bunched)	4	0	14	20
Carrots (topped)		0	210	270
Broccoli	1–2	0	14	21
Cabbages	14	0	150	180
Leeks		0	60	90
Lettuce		0–2	14	21
Mushrooms		0–1.5	5	7
Green peas		0	7	14
Spinach	1	0	10	14
Globe artichokes		0	14	21
Asparagus		0–2	14	21
Cauliflowers		0	21	28
Green onions		0	21	28
Low temperature, dry storage				
Garlic		0	180	210
Onions (dry)		0	30	240
Cold temperature, moist storage				
Green beans (snapbeans)	2	4–7	7	14
Okra	4	7–10	7	10

Bell peppers	3	7–13	14	21
Eggplant (aubergines)		8–12	7	7
Cucumbers		10–13	10	14
Watermelons		10–15	14	21
Cool temperature, moist storage				
Tomatoes (red)	2	8–10	8	10
Tomatoes (mature green)		12.5–15	14	21
Tomatoes (ripe)	3	13–21	4	7
Special conditions				
Dry beans		4–10	180	300
Pumpkins		10–15	60	160

Source: FAO, 2004.

The demand for cooling energy depends on the temperature of the product at the beginning of the refrigeration process; the target storage temperature (especially if the product is chilled between 1 and 7 °C); the ambient temperature (and, to a lesser extent, the micro-climatic circumstances of sunshine hours and mean wind speed); the total refrigerated space available; the product type; the bulk density of refrigerated products, the refrigeration technology (passive, sorption or compression); the energy efficiency of cooling equipment; the insulation characteristics of the storage facility; and the frequency of entries to the storage room.

Solar cooling can be combined with passive cooling[69] to provide a cheap and smart way to decrease storage temperature and save energy. Examples of solar storage technologies include:

- **PV-powered compression cold storage rooms with batteries** (Figure 4.29) are the most common solution and are largely available on the market. They are typically used for long-term storage between 0–15 °C and can operate for three to 7 days without sun.

- **PV-powered compression chillers with ice bank** can be operated by marketing cooperatives, or by large farmers for storage between 0–15 °C and can typically operate for one to 3 days without sun (Villgro, 2017; Press Trust India, 2014; Safarik, 2013).

- **PV-powered refrigerators with chemical storage** are typically used by small producers. They can operate at 0–15 °C without sun for no more than 3 days (Solarquest, 2015).

- **Solar thermal sorption refrigerators** (Figure 4.29) are usually not recommended for the vegetable chain as their stand-alone performance is only sufficient for very small volumes, such as to store vaccines (Critoph and Thompson, 1997).[70]

- **Passive cooling and sorption combined systems** are still in the R&D phase but have shown good results for long term storage between 0–15 °C (Islam, 2015).

69 Passive cooling is not a solar technology but a pro-poor technology that can be used especially in off-grid communities and for vegetable storage. It can extend shelf life by one to 3 days, with the combination of optimal harvesting time and water spraying where applicable, providing 5–6 °C lower temperature than ambient (Kitinoja, 2013).

70 This technology has become largely commercial over the last decade but is unsuitable for larger applications under 4 °C.

TABLE 4.21. Suitability of vegetable cooling technologies for use with solar energy, sorted by storage temperature ranges.

Storage temperature range	Technologies/solar energy	Energy demand per tonne of product	Target producer groups
Few degrees below ambient temperature. More a good practice than a technology.	(i) Field packing of leafy, stem, or fruit vegetables, root, tuber and bulb crops. (ii) Passive cooling from selecting the coolest harvesting time of day and use of shading and water spraying. (iii) Autonomous technology, with no input of solar energy.	< 1 kWh/tonne	All, including subsistence farmers
15 °C to 20 °C Basic-intermediate technology	(iv) Pre-cooling and evaporative cool storage. Autonomous, without solar. (v) Sorption refrigeration/solar thermal, ventilation needs external grid electricity or solar PV. (vi) PV-powered compression cooling, autonomous with electricity and ice banks.	< 20 kWh/tonne	All farmers; SMEs; Medium-scale producers and cooperatives
0 °C to 15 °C Intermediate technology	(i) Sorption refrigeration/solar thermal (ii) Compression cooling/solar PV	20 to 100 kWh/tonne	SMEs; Medium-scale enterprises/ cooperatives
Below 0 °C Advanced technology	Automated packing house operations; pre-cooling and cold storage for any kind of fruits and vegetables/solar PV assisted	> 70 kWh/t	Large-scale producers, processors, cooperatives

Source: USAID, 2009; FAO, 2004.

FIGURE 4.29. Examples of a passive chiller, solar thermal refrigerator and solar PV-powered cold storage room.

Source: Berney, 2008; Kininoja, 2013; Safarik, 2013.

COSTS

CBAs taking possible revenue into account are highly specific to location, product, season, and market. Likewise, any additional income generated by introducing cold storage shows extreme fluctuations, depending mainly (i) on the amount and type of product otherwise lost without cooling, and (ii) the actual and longer shelf life market price of the particular product. Typical capital and operational costs for solar cold storage systems vary widely as well (Table 4.22).

TABLE 4.22. Capital and operational costs of different solar cold storage systems.

Technology	Main cost elements	Capital (manufacturer) (US$/tonne)	Operation and maintenance (US$/tonne/year)
PV-powered compression cold storage rooms with batteries	Insulated container, PV modules, wiring, inverter, compressor, batteries	5,000 (SunDanzer) 16,000 (Sunfrost) 40,000 (ColdHubs)	~500
PV-powered compression chillers with ice bank	Insulated container, PV modules, wiring, inverter, compressor, ice storage	1,800 (Ecozen) 9,000 (ILK)	450–1,000
PV-powered refrigerators with chemical storage	Insulated refrigerator, PV modules, wiring	16,000 (SunDanzer)	Negligible
Solar thermal sorption refrigerators	Solar collector, partly metal chamber, metal frame	2,000 (low-tech) 12,000 (high-tech)	Negligible (low-tech) 100–200 (high-tech)
Passive and sorption combined systems	Mainly for sorption refrigerator as above	No data	No data

Source: Authors.

MAIN IMPACTS

The main benefit of adopting cold storage, either solar or grid-powered, is the possibility of commercializing higher-quality food products through proper storage and treatment. This is especially relevant for operators living in rural grid areas where grid electricity is unreliable or not available at all. The possibility of lengthening the time when the product is placed on the market. For example, the operator can decide to wait a few days to sell the vegetables in anticipation of a better market price or to avoid price deterioration. Both possibilities will likely translate into additional income from the sale of refrigerated products, with additional income coming from sales of perishable products that would otherwise have been wasted or required storage space rental.

A benefit of solar cold storage (Table 4.23) is the independence from grid-power and fossil fuels, decreasing GHG emissions. Surplus electricity generated by solar energy systems (if any) can also be sold to improve local access to energy (thus allowing the establishment of new businesses or the availability of new modern energy services), and/or help save on electricity purchases. This latter saving is determined by local energy prices, local discount rate, and the turnkey price of a solar cold storage system (Milhoff, 2013).

Cold storage systems that are able to cool down below 15 °C are generally more capital intensive than conventional refrigeration applications, but their operation is significantly cheaper and mainly limited to maintenance. The only major maintenance expense is for those systems that use batteries, which need replacing after six or seven years.

As refrigerated products need additional care, supervision and logistics, they generate employment. When compared to conventional refrigeration cooling from the grid, solar energy utilization creates more than twice as many jobs (Shahan, 2013).

The environmental implications of such systems are minor, the main risk being associated with lead-acid batteries that need recycling or disposal at the end of their life time to avoid pollution. In addition, the technology will normally require water for cleaning.

For using solar systems at times of low or zero solar radiation, energy storage from cool store insulation, ice banks or batteries is possible but need extra engineering and costs.

Pro-poor applications using low-cost passive cooling systems only provide lower temperatures of just a few degrees below ambient and hence give only moderate shelf life extension. Solar cold storage systems that perform similarly to conventional systems, are very capital intensive.

The impact of solar cold storage on gender equality in any one context, at the farm and cooperative level, will depend on the roles, access to inputs, and decision-making of men and women in production, processing and marketing. In general, gender-sensitive interventions in vegetable value chains require concerted efforts to empower women and women's groups.

TABLE 4.23. Main advantages and disadvantages (solar-powered cold storage systems).

Advantages	Disadvantages
• Access to energy in off-grid or unreliable grid areas. • Decreased GHG emissions due to offsetting fossil fuel or grid electricity powered cold storage. • Farm income diversification (due to possible storage space rental). • Extended shelf life strengthens market position for the vegetable producer and contributes to avoiding food waste. • Generation of employment due to additional care, supervision and logistics.	• Ice banks or batteries may be needed that require extra engineering and costs. • Pro-poor applications using low-cost passive cooling systems only provide lower temperatures of just a few degrees below ambient. • Solar cold storage systems that perform similarly to conventional are very capital intensive. • Water needed for washing the equipment.

Source: Authors.

Although a technology description and information on costs and expected co-benefits is reported in this study, the methodology has not been applied to a specific real case study since no first-hand information on a commercial application of this technology could be found by the time of the study.


Source: © GIZ/Kerstin Lohr

4.2.2. SOLAR-POWERED WATER PUMPING

In remote rural areas grid electricity is often not available and fossil fuels are costly. Solar irrigation systems allow for coping with such circumstances.
Source: © GIZ/Fehrenbach

Solar water pumping is an established and mature technology that provides a good alternative to using internal combustion engines (ICE) or grid electricity to power water pumps. Performance of the solar PV modules depends on the average and seasonal levels of solar irradiation in the location. Therefore, PV systems have to be designed to suit the location where they will be installed.

Solar PV technology is particularly relevant for remote rural areas where grid electricity is not available or where diesel, LPG and gasoline fuels to power ICEs are costly. A solar-powered water pumping system consists of the following elements (FAO and EBRD, 2017):

- **Array of solar PV modules** that collect solar radiation and convert it into DC electricity. The PV panels can be installed on a roof, freestanding tower or directly on land. The installed capacity (kW) is determined by the power requirements of the water pump and the mean average solar radiation level.

- **Inverter** that converts DC electricity to AC with minimum loss. An inverter is not needed if a DC motor is used. Inverter capacity depends on the installed PV power capacity and the motor power demand to drive the pump. An inverter is needed for AC stand-alone and grid-connected systems.

- **Controller,** the electronic interface device between PV modules and pump, that is needed to automatically start/stop the pump according to available solar irradiation. A water level sensor is often attached to the controller to prevent dry-running the pump.

- **Water pump,** often a submersible design, that has to be maintained every three to five years. It supplies the irrigation distribution system with water under pressure, or adds water to the storage tank or reservoir for gravity feed.

Power requirements depend on the pumping head and the maximum volume of water required per hour during the irrigation season, which is a function of the crop requirements and water quality. An irrigation system distributes water according to the volume required by the soil, crop type, growth stage and area covered. The frequency of application depends on the evapotranspiration rate, which is a function of local climate, soil type, crop type and maturity. Given the tendency for lower pumping pressures of solar energy systems compared with conventional ones, the irrigation system designs are typically combined with gravity storage to increase head and/or micro/drip-irrigation, which functions at lower pressures compared with sprinklers.

Some systems include a water reservoir to store the pumped water. This can help lower the pumping capacity requirements of the pump and offset variable outputs due to cloud cover and darkness. Automatic sensors of soil moisture, radiation and flow sensors, as well as control of battery charge levels and solar trackers improve water use efficiency but are not common in developing countries.

Two main technological solutions exist:

(i) The electrical pump is directly connected to the PV panels and operates when there is enough solar radiation to produce sufficient power. This requires a reservoir or tank for storing water (Figure 4.30) if irrigation is needed for cloudy days and at night. This solution applies to low pressure or gravity irrigation systems and normally is an alternative to stand-alone diesel or LPG ICE powered pumps (LPG stands for liquefied petroleum gas).

(ii) The electrical pump is powered using grid electricity and the PV system compensates for when the grid goes down. When not supplying electricity to drive the pump (such as after rainfall), the surplus electricity generated by the PV system can be sold to the grid (for instance under an FiT policy), thus increasing the return on investment for the system owner.

FIGURE 4.30. PV powering a submersible water pump:
Water is then pumped to a storage reservoir ready for distribution
under gravity for irrigation or local water supply when neelrr257(G s)277(T)-212720(eser)-30 whey d279.2795 cm0 0 m.10(w)

COSTS

Solar PV water pumping systems need to be technically and economically feasible in order to challenge conventional water pumping systems. Comparative costs depend on crop type, soil type, location,[71] water table, grid electricity prices, government incentives, design of PV system, development of the technology, and regulations or carbon charges on GHG emissions (Kelley et al., 2010).

Costs of PV water pumping systems include equipment, maintenance and operations, and savings on fossil fuel costs (Table 4.24). The higher upfront capital cost for PV compared to conventional pumping systems is a major constraint but the present trend in rapid reduction of PV panel prices is making the systems competitive. Over a full lifecycle analysis, solar PV can be a better option. The cost of a water pumping system depends on component prices, insolation levels, finance interest rates, diesel fuel costs and labour costs, which vary with time and place of application (Senol, 2012).For instance, Table 4.24 summarizes a comparison of main costs related to electric, diesel, LPG and PV pumps in Morocco, where LPG is highly subsidized (FAO and EBRD, 2017).

TABLE 4.24. Comparison of costs for electric, diesel, LPG and PV-powered water pumping systems to meet an electricity demand of 100 kWh/day for water supply needs in Morocco.

Energy Source	Electricity	Diesel	LPG (butane)	Solar PV
Energy yield (kWh/day)	100	100	100	100
Cost per unit of fuel (US$/kWh)	0.12	0.10	0.02	0
Fuel cost per day (US$/day)	11.8	10.4	2.5	~0
Fuel cost per year (US$/year)	4,294	3,811	907	~0
Operation and maintenance	600	1,200	1,000	1,000
Initial capital cost (US$)	2,400	2,400	2,400	16,800

Source: FAO and EBRD, 2017.

MAIN IMPACTS

Solar PV systems can supply water where the grid is unreliable or in off-grid areas by replacing diesel generator-based water pumps. Solar PV systems also ensure that water can be supplied during dry seasons. This can facilitate continuous cropping rotations, improved crop yields and the introduction of higher water-demanding crops

71 For instance, water demands vary with changes in humidity that influence the water requirements of a crop; variability in solar radiation that impacts the efficiency of a PV system; and evapotranspiration resulting from increases in ambient temperature. Also, the depth of the water source (from groundwater or waterways) is an important factor since a decline in the water table increases the nominal power requirement of a pump (Mekhilef et al., 2013).

with higher market value. Therefore, farm incomes can be increased and opportunities created to promote local development by strengthening local agrifood value chains. Solar PV systems are a particularly cost-effective option when they are combined with drip irrigation to maximize water use efficiency. According to some farmers, the solar irrigation pump reduces their time required for pumping compared to petrol pumps, which require the farmer to be fully engaged in the activity. Furthermore, as PV modules provide shade, less sun-tolerant plants can be grown underneath.

Disadvantages (Table 4.25) are linked to the higher capital cost; lack of relevant infrastructure support in some rural areas; and risk of theft of the equipment. One possible risk is due to the overexploitation of water since farmers tend to pump more water with solar energy systems than with conventional fuel or electricity-powered systems, since once the system is in place, they perceive water pumping to be essentially free. This impact has yet to be fully demonstrated, however.[72] Maintenance of solar energy systems requires skilled technical staff who are not always available in rural areas, This can potentially delay repairs and regular maintenance. Finally, PV panels will require more space compared to a diesel/petrol pump, probably agricultural land.

TABLE 4.25. Main advantages and disadvantages of solar-powered water pumping systems.

Advantages	Disadvantages
• Can maximize water use efficiency when combined with drip irrigation. • Is designed to better accommodate borehole/well yield and thus can avoid excessive pumping and waterway cavitation. • No GHG emissions. • Can be operated off-grid or in areas with an unreliable grid. • Reduces farm variable expenses and can improve incomes. • Reduced time spent in the pumping activities. • Low maintenance requirements. • Low labour requirements.	• Needs careful design for specific crops and locations. • Risk of overexploitation of underground water due to the free energy source. • High initial capital investment. • Maintenance requires skilled staff who may not be locally available. • Land requirement from solar panels. Maintenance requires skilled staff who may not be locally available. • Vulnerable to theft. • Land requirement from solar panels. • Vulnerable to theft.

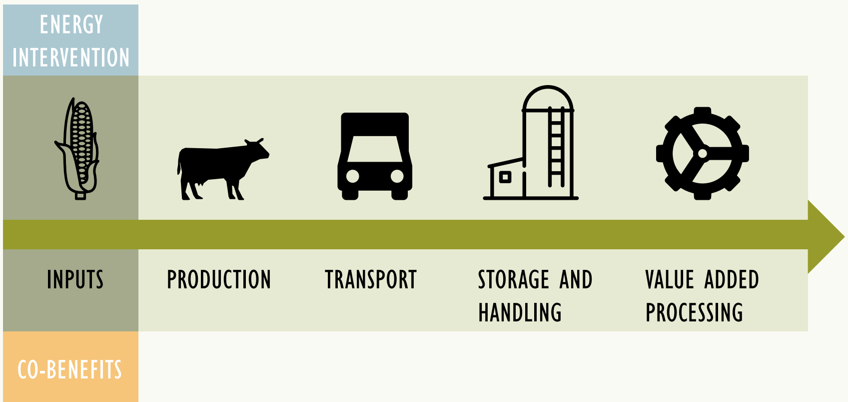
Source: Authors.

72 In certain contexts, solar pumping can limit water overexploitation since the systems are usually designed to fit the water yield of the borehole or well due to the systems' high capital cost. Moreover, since solar pumps can deliver water for a maximum of 8 h/day, their daily water extraction is limited, unlike diesel or grid powered pumps. According to GIZ experience on the ground, when PV pumps substitute conventional pumps, they usually do not result in more water pumped per day.

CASE STUDY: SOLAR-POWERED WATER PUMPING FOR VEGETABLES IN KENYA

FIGURE 4.31. Location of the intervention and co-benefits of solar water pumping in the value chain.

Source: Authors.



Futurepump Ltd. is a provider of a solar powered irrigation pump – the SF1 – developed in cooperation with the PRACTICA Foundation and iDE. It was designed specifically for the needs of smallholder farmers with less than 0.5 hectares of total land area. The company has mainly targeted the Kenyan market since its establishment in 2012, and REEEP has supported the company's efforts to enter the market. Futurepump's mission is to bring affordable and sustainable irrigation products and services to smallholder farmers. Futurepump has been supported by PAEGC since 2013.[73]

The company is currently seeing surging demand across East Africa and is initiating sales in other countries like Uganda and Rwanda through several distribution partners. The company offers a rent-to-own payment plan that enables customers to pay for the pump in instalments over approximately 18–24 months. The first larger consignment of SF1 pumps was brought to market in January 2016. To date, Futurepump has sold over 1,000 pumps in Kenya and other East African countries.

Feasibility analysis

To improve the livelihoods of small farmers and to meet growing demand for food in the region, Kenyan farmers need more flexible and reliable irrigation methods as well as more control over the timing of irrigation. Most agriculture in Kenya is rain-fed with two growing seasons. A large part of the population is dependent on agriculture for living. Farmers face a number of challenges ranging from unreliable rainfall to high and volatile energy prices, low crop yields and lack of access to modern energy technologies. According to estimates, there are 2.9 million smallholder farmers in Kenya with only 6 percent of the farmland being irrigated. Most water pumping technologies require energy inputs but in turn can contribute to an increase in yields. Small-scale water

73 For more information see https://poweringag.org/innovators/solar-powered-pumps-improved-irrigation.

pumping systems based on solar energy can provide a viable alternative to manual and fossil fuel-based pumping. Currently, fuel-powered irrigation pumps power the expansion of irrigated land, increasing CO_2 burdens and particulate matter pollution.

As in most developing countries, agriculture is the mainstay of Kenya's economy, directly contributing 26 percent of GDP, and an additional 25 percent indirectly. The sector accounts for 65 percent of the export earnings, provides more than 18 percent of formal employment and more than 70 percent informal jobs in rural areas. The opportunities for growth through irrigation are immense in Kenya. According to its irrigation policy, the country has an irrigation potential of 1,341,900 ha based on available water resources and improvement in irrigation water use efficiency. Of this potential, approximately 161,840 ha of irrigation are already developed. The rate of irrigation development in the country has been low, with an increase of new irrigated area equivalent to an annual growth rate of less than 1 percent. The specific objective of Kenya's national irrigation policy is to expand land under irrigation by an average of 80,000 ha/year to reach the full irrigation potential by 2030. This target will not be met unless the potential of the small-scale farming sector is adequately addressed.
Of the currently 161,840 ha of irrigated lands, individual smallholder farmers count for around 42 percent. With population growth and increased pressure on arable land, smallholder farmers will increasingly demand viable options to irrigate their land.

Solar water pumping interventions are far less known in the Kenyan market in comparison to technologies like manual and petrol/diesel pumps. Visibility through farmer-to-farmer demonstration, word-of-mouth, seeing the pump in use by well-respected farmers, demonstration at local markets, and easy, trustworthy warranty as well as technical assistance have shown to be effective ways to raise interest, brand awareness and trust in the technology among typically risk-averse smallholders in Kenya.

Description of the energy intervention

The SF1 solar pump (or Sunflower pump) consists of three main elements: the solar PV panel (80 W), the engine, and the pump (Figure 4.32). The PV panel generates electricity that drives a DC motor to turn a flywheel that pumps up to 12,000 litres of water per day from a depth of 6 m. One pump enables the farmer to irrigate approximately 0.2 ha of land. The pump can pump water over a distance of more than 100 m with minimal loss of flow. This makes it suitable for pumping into elevated storage tanks or directly into drip irrigation system.

FIGURE 4.32. The SF1 solar pump.

Source: left: Authors; right: GIZ/Katharina Meder.

Financial CBA

Benchmark scenario

The majority of Futurepump's existing customers in Kenya already irrigated prior to purchasing the SF1 pump. Furrow irrigation is the most common irrigation method and the pump would most often be replacing either a petrol, diesel or manual pump. Approximately 25 percent of the land covered would not have been irrigated at all. For the purposes of this case study, the baseline assumes that the solar pump replaces a petrol pump, since most Futurepump customers who already irrigated their land used a petrol pump.

The study assumes that a typical farmer buying an SF1 pump would be smallholder farmers with 0.2–0.6 ha of total land. They produce crops for own consumption and/or for sale at the local markets and would not typically be connected to structured value chains. In the study, 30 percent of the maize yield is assumed to go towards own consumption, with the rest being sold in local markets.[74]

The types of crops and yields vary considerably depending on specific farming practices, as well as on preferences and experience of the farmers. However, typical crops and average yields based on information gathered from 38 current Futurepump customers have been used as the basis for yield estimates for each crop.

Cultivating a mixture of crops, intercropping and crop rotation are common practices for Futurepump customers. Maize, tomatoes and cabbage are all commonly grown crops.

The following assumptions regarding the plot have been made: out of a 0.4 ha plot, the farmer grows maize on 0.2 ha, and the remaining 0.2 ha are used for tomatoes and cabbage that are sold in local markets. Maize is rain-fed, while the other crops are

74 Most of Futurepump's current customers are in the counties near Kisumu in western Kenya. All assumptions made in this study are based on indications provided by smallholder farmers in that area and data collected in their farming environment.

irrigated. Fertilizers and pesticides are commonly used. Associated costs have been assumed in this study for both the baseline (petrol pumps), as well as the SF1 pump scenario.

The following assumptions were made in the CBA:

- **Interest rate:** As in the cases of the biogas for power plant and the MilkPod, the selected discount rate for the financial analysis is 11 percent (which reflects the interest of 9-year government bonds).

- **Life expectancy of the technology:** The expected lifetime of the equipment is 10 years.

- **Scale:** The SF1 can pump up to 12,000 litres of water per day from a depth of 6 meters. This is enough water to irrigate approximately 0.2 ha of land.

Costs

Capital cost: The Sunflower pump costs US$650 when purchased in cash.[75]

Maintenance costs: The Sunflower pump comes with a two-year warranty. Within this period all costs for maintenance (other than damage that voids the warranty policy) are covered by Futurepump. This includes a monthly service check by technicians, any additional call-outs and spare parts. The costs for Futurepump in this period are estimated at US$100/pump over the warranty period. After this time, these costs will be paid by the farmer and are estimated to be US$33/year – including technician call-outs and spare parts. The most common spare parts for replacement are flywheel rubber, Teflon (which is to be replaced by a more durable graphite rope), and occasional bearings, panel connections/wires and springs.

The overall lifetime maintenance and repair costs (assuming a ten-year life expectancy of the technology) are estimated at US$364. For the baseline (petrol pump), no maintenance costs have been assumed. Smallholder farmers would typically not invest in repairing the pump if it would fail, but instead replace it with a new one.

Operating costs: The SF1 pump does not have any fuel costs; therefore, the only operating costs for using the pump are labour costs. These are outlined in Table 4.26.

Based on interviews with 38 Futurepump customers, farmers typically irrigate 2–3 times a week during the dry season for an average of 6 hours/day. Water pumping is required during a cumulative period of approximately 34 weeks a year, with 102 irrigation days a year. It is assumed in this study that during these 34 weeks, farmers irrigate 3 times/week.

Pumping with the SF1 solar pump requires more time compared with a petrol pump. However, based on interviews, fuel savings make the switch to a solar pump worthwhile. Also, farmers have indicated that the solar pump in fact reduces the total

75 Futurepump offers a rent-to-own payment plan with a repayment period of approximately 24 months with an annual percentage rate of 22 percent. An upfront deposit is charged. The level of deposit and the repayment period is negotiated with each customer. The interest cost of the loan has not been calculated in the financial CBA.

time required for pumping. It can be left to pump on its own, whereas a petrol pump requires the farmer to be physically present and engage in the pumping activity itself, albeit for shorter pumping periods. On an annual basis, the solar pump enables the farmer to spend 113 hours on other activities.

Both family labour and hired labour are used on smallholder farms. In addition to family labour, a farmer would typically hire a person to take care of the farm for irrigation and other tasks during the dry season. The cost for labour is estimated at about US$4.95 (KES500)[76] per day. Although water pumping may be conducted three times a week, according to Futurepump, outside labour would be hired for 2 days a week on average. On an annual basis, hiring a worker twice a week adds up to US$336. Labour would be required by a farmer regardless of the water pumping technology employed.

Land costs: Typically, Futurepump customers own their land and would thus not incur rental costs.

Benefits

The capital cost of the PV pump (US$650) is significantly higher than for a petrol pump (US$250). However, the lifetime of the solar pump is ten years, whereas a petrol pump typically lasts only around three years. During the ten-year investment period of the study, the farmer would thus be able to save the capital investments costs of another two petrol pumps, with a related net savings of US$288.

The only operating costs related to the PV pump are labour costs. The farmer is able to save on the fuel costs for irrigating the land with a petrol pump. Futurepump has estimated the water requirements for irrigating 0.2 ha of land (based on data on water pumping habits of smallholder farmers in the Kisumu area). A little more than one hour is needed to pump the required amount of water with a petrol pump. Approximately 85 litres of petrol are consumed annually. The related fuel costs savings are US$82/year with the current price of petrol (ERC, 2016).

Replacing a petrol pump with a solar irrigation pump does not affect the yields as irrigation is practiced before the point of investment for the PV pump. The capital cost and operation cost savings do however positively influence cash flow through the reduction of overall costs of farming inputs.

Financial profitability

The cash flow in the benchmark scenario (petrol pump) shows a negative net financial result for a smallholder farmer using a petrol pump. The average loss is slightly more than US$10 each year (up until year five) and up to US$20–30 during the latter half of the ten-year investment period.

In comparison, for a smallholder farmer using an SFI pump, the cash flow shows a positive balance throughout the whole investment period (being highest in year one at US$74 when the maintenance costs are covered by Futurepump).

76 Assuming KES1 = US$0.01.

The negative cash flow in the benchmark scenario could be balanced by the farmer by periodically reducing some farming input costs in order to avoid a loss. However, with the assumptions used in this study, the financial NPV for the farmer adopting the solar-powered water pump is positive (US$331) over the lifetime of the technology (ten years).

TABLE 4.26 Financial CBA of a solar-powered water pump over 10 years compared with benchmark.

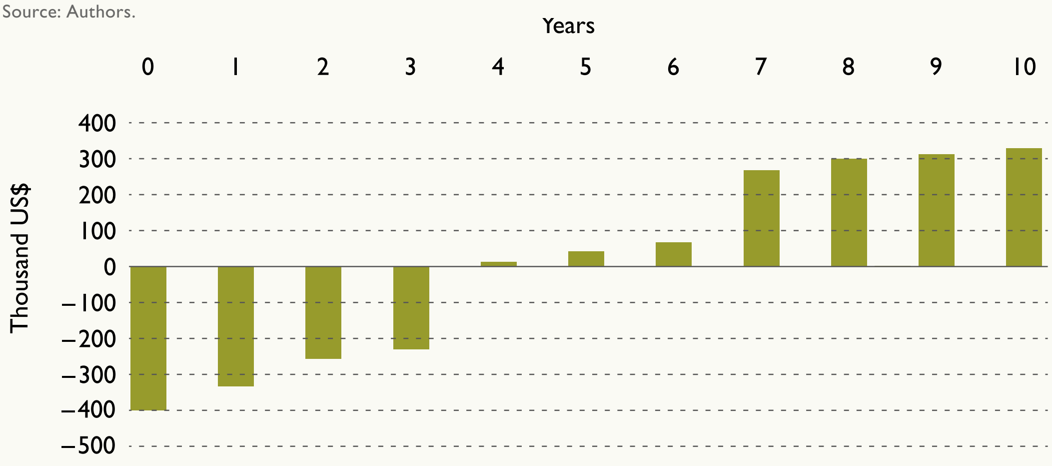
	Unit	Sunflower pump	Benchmark	Notes
Life expectancy of the technology	year	10	3	
Financial costs				
Capital cost	US$	650 (every 10 years)	10,500	Pers. comm. SDG
Maintenance costs	US$/year	33	0	Year 1 and 2: US$0
Labour costs	US$/year	337	337	US$4.95/day
Other operating costs	US$/year	0	82	Fuel cost (ERC, 2016)
Financial profitability indicators				
NPV	US$	331		
IRR	%	27		

Note: A discount rate of 11 percent was adopted for the financial CBA.

Source: Authors.

FIGURE 4.33. Cumulative discounted net financial benefits over 10 years (solar-powered water pump).

Source: Authors.



Economic CBA

Value added along the value chain

Futurepump's current customers would mostly already irrigate, so the introduction of new pumping technology for irrigation water would not have an impact on yields.

These farmers typically sell products directly to end consumers at local markets. The farmer's value added to the vegetable value chains would thus only be impacted by the reduction in cost of inputs for farming activities. There is no impact on the subsequent steps of the vegetable value chain.

Subsidies and taxes

The effect on positive cash flow of the farmer will increase government VAT revenue due to increased private spending. In this study, 50 percent of excess cash available each year is assumed to be recirculated into the formal sector as purchases, which are subject to VAT. The trend in VAT revenue through private spending is decreasing due to lower producer price inflation in comparison to consumer price inflation, negatively affecting the farmers' long-term spending power.

Kenya is supporting the growth of solar markets in the country by offering an exemption from the 16 percent VAT and a zero-rated import duty for solar products. For the Sunflower pump, the related tax revenue would be US$104/pump in terms of VAT. Other costs related to import of technologies into Kenya are the Import Declaration Fee (IDF), which is 2.25 percent of the value of the goods; handling charges assessed by the Kenya Port Authority (KPA); and the Railway Development Levy (RDL), which is 1.5 percent of the total value of goods. For a full container with 160 pumps, the related tax revenue adds up to US$2,800 for a shipment – or US$16.97/pump. In addition, Futurepump is relying on services of a customs clearance agency for the administration and logistics of the pumps through customs and into the markets. Thus, they contribute to additional VAT revenue of US$82/full container of pumps.

Petrol pumps are not exempted from VAT and related tax revenue is US$40/pump. The price of petroleum products is determined by ERC using a formula that guarantees a certain profit margin for petroleum dealers. The share of taxes and fees is not adjusted based on fluctuations in global fuel prices. The share of tax of the current price for petrol is US$0.38/litre (The Star, 2016). The related tax revenue from fuel consumption for irrigating the smallholders land with a petrol pump is US$32 per year. Petrol is not subsidized for end users in Kenya and the customs value of petrol pumps is not known. As an estimate, in this study the ratios between sales value and customs value have been assumed to be the same as for the PV pump. The IDF (2.25 percent), KPA and RDL (1.5 percent) import related tax revenue add up to US$6.50/pump.

The incremental tax revenue from imported technology is US$29 in year zero, US$58 in year four and US$69 in year seven – due to lost VAT revenue and import duties from sales and importation of petrol pumps.

Smallholder farmers are currently not taxed in Kenya. Therefore, no tax revenue is assumed from the sales of the yield.

Reduced tax revenue from fuel: The current fuel tax in Kenya is US$0.38/litre of petrol. The related tax revenue for annual fuel consumption of the farmer using a petrol pump is US$32. The tax consists of a road maintenance levy (RDL), excise duty, petroleum development levy, petroleum regulation levy, fuel storage facility charges and an excise duty remission (The Energy Act, 2006, Supplement No 88, 2010). The

RDL earmarked for road maintenance is treated as a benefit to society in the baseline scenario and is US$0.18/litre of petrol, or US$15 for the annual fuel consumption of the farmer. The remaining tax share is assumed to be used mainly towards costs of governance, development and national infrastructure for the fossil fuel sector at large, and is therefore treated as neither a benefit nor a cost.

Avoided cost of local infrastructure and service provision for fossil fuel sector: While the national costs of supporting the fossil fuel sector are covered by the fuel tax, the cost for local government infrastructure and service provision is estimated at US$1–2 for the annual fuel consumption of the farmer (UNEP, 2016).

Avoided cost of local externalities caused by fossil fuel consumption: Fossil fuel consumption by the farmer results in a negative impact on health, mortality, congestion, accidents, etc. The level of tax which would cover the cost of such impacts has been estimated by UNEP as a corrective tax of US$0.36/litre of petrol. The farmer's annual consumption of petrol is estimated at US$31/year; a cost that is avoided with the adoption of solar technology.

Avoided cost of global externalities caused by fossil fuel consumption: The corrective tax rate of global damages from fossil fuel consumption through its effect on climate change has been estimated by UNEP (2016) at US$0.08/litre of petrol. The farmer's annual consumption of petrol has been estimated at US$7/year; a cost that is avoided with the adoption of solar technology.

Assessment of environmental and socio-economic impacts

Soil quality

Impact	Relevance
No impact	–

Fertilizer use and efficiency

Impact	Relevance
No impact	–

Indoor air pollution

Impact	Relevance
No impact	–

Water use and efficiency

Compared to the use of petrol pumps, the adoption of solar pumps does not have an impact on water use or water efficiency at the farm. Some farmers may combine the irrigation solution with a drip irrigation system, which would decrease water use. This is however independent from the pumping solutions per se and Futurepump does not offer a drip system. Furrow irrigation continues to be the most common irrigation method among Futurepump farmers.

Impact	Relevance
Negligible	–

Water quality

Impact	Relevance
No impact	–

Food loss

Impact	Relevance
No impact	–

Land requirement

Land occupied by a PV pump is usually larger than the amount occupied by a conventional petrol pump. Land occupied is typically agricultural land, which is therefore not available for other uses. Regardless, the overall impact is negligible, since the areas at stake are small. The PV pump itself occupies a land area of maximum 0.6 m^2 depending on the positioning of the solar panel.

Impact	Relevance
Negligible	–

GHG emissions

In the baseline scenario, the farmer using a petrol pump is estimated to use 85 litres of petrol per year, with annual GHG emissions of 0.2 tCO_2eq. The corrective tax rate, which would cover both local and global externalities, has been used for internalizing the costs of GHG emissions in Kenya. As for the other case studies, the corrective tax estimates are based on a social cost of CO_2 provided by the EPA (2016) of US$36/tonne (with a 3 percent average discount rate) – in line with the IMF (2014) estimate of US$35. The avoided global and local damages related to GHG emissions amount to about US$38/year/pump.

Impact	Relevance
Positive	Low

Access to energy

Although most of the Futurepump customers would already have access to modern energy in the form of petrol pumps, the solar pump increases access to electricity. In fact, the PV pump includes a USB mobile phone charging unit, which can be used on days when irrigation is not needed. In this study, it is assumed that an average household would charge their phone twice a week (GSMA, 2011) using a cell phone charging service with a related cost of US$0.20/charge (GVEP, 2012; Futurepump, 2016). Related annual savings are US$21/year for the farmer.

Impact	Relevance
Positive	Low

Household income

Most farmers purchasing a solar pump are already irrigating. Thus, introducing new pumping technology for the irrigation water does not have any impact on yields that would increase the revenue from crop sales. As considered in the financial CBA, avoided fuel costs from switching from a petrol to a solar pump do however leave an additional US$82/year for the household.

Impact	Relevance
Positive	High

Time saving

Pumping water with the PV pump requires less time in comparison to irrigating with a petrol pump. According to some farmers, the solar irrigation pump reduces their time required for pumping as the pump can be left to operate on its own. In contrast, a petrol pump requires the farmer to be fully engaged in the pumping activity itself. On an annual basis, this frees up 113 hours for other activities at the farm. Since it is not possible to know whether these hours would be used for productive activities or not, we do not monetize them.

Impact	Relevance
Positive	Low

Employment

No extra employment is created at the farm in comparison to the baseline.

Employment is however created within the clean energy markets through jobs in sales, operational and financial management, installation, maintenance within the company itself, as well as within Futurepump's network of distributors and retailers.

Futurepump currently has a staff of 20 people with the majority based in Kenya. Since expanding their sales in Kenya (February 2016), Futurepump has sold over 1,000 pumps in East Africa and over 300 in Kenya alone. In the long run, the employment created by distributors, retailers and logistics are likely to be more significant. The company is roughly estimating that one technician can support the maintenance of 20–30 pumps. Futurepump is offering on-the-job training in sales and technology to its direct employees as well as to its distributors and retail partners. Thus, they contribute to skills development within the country.

Having estimated the wage of a technician in Kenya to be US$150–200/month or around US$2,000/year, US$70/pump/year would be the wage associated with the commercialization and maintenance of one PV pump.

Impact	Relevance
Positive	Moderate

TABLE 4.27. Summary of environmental and socio-economic impact (solar-powered water pump).

	Indicator	Impact
	Soil quality	No impact
	Fertilizer use and efficiency	No impact
	Indoor air pollution	No impact
	Water use and efficiency	Negligible
	Water quality	No impact
	Food loss	No impact
	Land requirement	Negligible
	GHG emissions	US$38/year (196 kg CO_2eq/year)
	Access to energy	US$21/year (from Tier 0 to Tier 1)
	Household income	US$82/year (considered in financial CBA)
	Time saving	113 hours per year
	Employment	US$70/year (1 new job for every 30 pumps sold)

Note: green = positive impact, yellow = variable impact, red = negative impact.

Source: Authors.

Assessment of economic profitability

As described in the subsidies and taxes section, the economic CBA of the solar-powered water pump over 10 years is strongly influenced by variations in tax revenues from import, fuel and VAT. Moreover, global and local damages due to avoided GHG emissions, savings on use of cell phone charging services due to increased access to energy, and employment creation are additional monetized environmental and socio-economic benefits – all of which contribute to a very positive economic NPV (Table 4.28 and Figure 4.34).

TABLE 4.28. Economic CBA of the case study (solar-powered water pump).

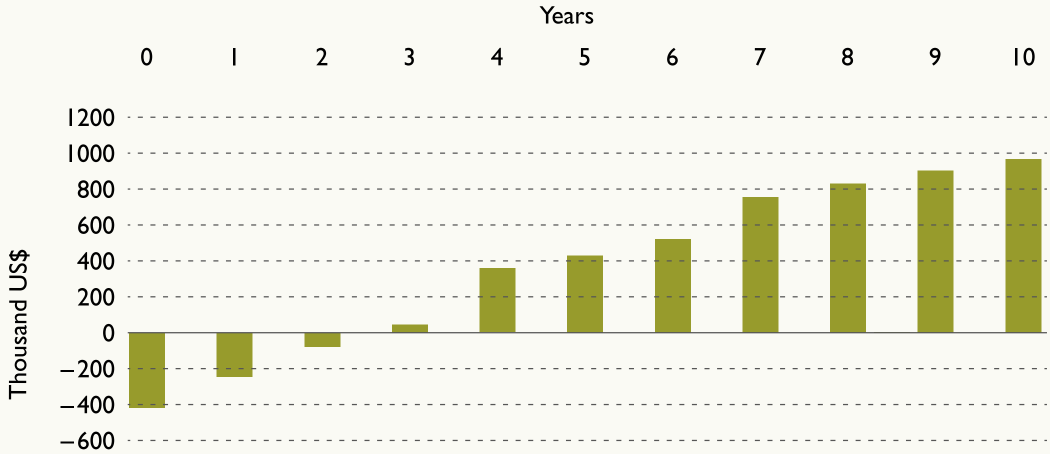
	Unit	Value	Notes
		Economic costs	
Missing tax revenue – fuel	US$/year	32	ERC (August, 2016)
Net tax revenue – imported tech	US$	29 (Year 0) 58 (Year 4) 69 (Year 7)	Kenya Revenue Authority (KRA, 2016), Futurepump

	Unit	Value	Notes
		Economic benefits	
VAT revenue – private spending	US$/year	6 (Year 1) 3 (Year 2–6) 2 (Year 7–9) 1 (Year 10)	REEEP's calculation
Avoided costs of infrastructure and services facilitated by local governments	US$/year	1 (Year 1–5) 2 (Year 6–10)	UNEP, 2016
		Environmental and socio-economic benefits	
Avoided GHG emissions	US$/year	38	UNEP, 2016, Futurepump
Savings on use of cell phone charging services due to increased access to energy	US$/year	21–35	GSMA (2011), GVEP (2012), Futurepump (2016)
Employment	US$/year	70	Assuming that one job is created with every 30 pumps sold (estimate based on interview with Futurepump)
		Economic profitability indicators	
NPV	US$	960	
IRR	%	51	

Source: Authors.

FIGURE 4.34. Cumulative discounted net economic benefit over 10 years (solar-powered water pump).

Source: Authors.



Results

The farmer's discounted financial benefit is between US$25–160 annually as a result of avoiding fuel and technology re-investment costs. The additional economic benefit for society results from avoiding climate change-related global as well as local damage (health, accidents, congestion, etc.), increased access to electricity for cell phone charging, employment creation, and increased VAT revenue from private spending by the farmer.

In years zero, five and eight of the investment period, the missing tax revenue from imported petrol pumps results in a slight negative shift of the economic benefits. For the ten-year investment period, however, the economic benefit is greater than in the baseline scenario.

Moreover, the solar-powered water pumping releases about 113 hours/year that can be used for (productive) activities other than pumping and that have not been monetized.

FIGURE 4.35. Cumulative discounted net financial and economic benefits over 10 years (solar-powered water pump).

Source: Authors.

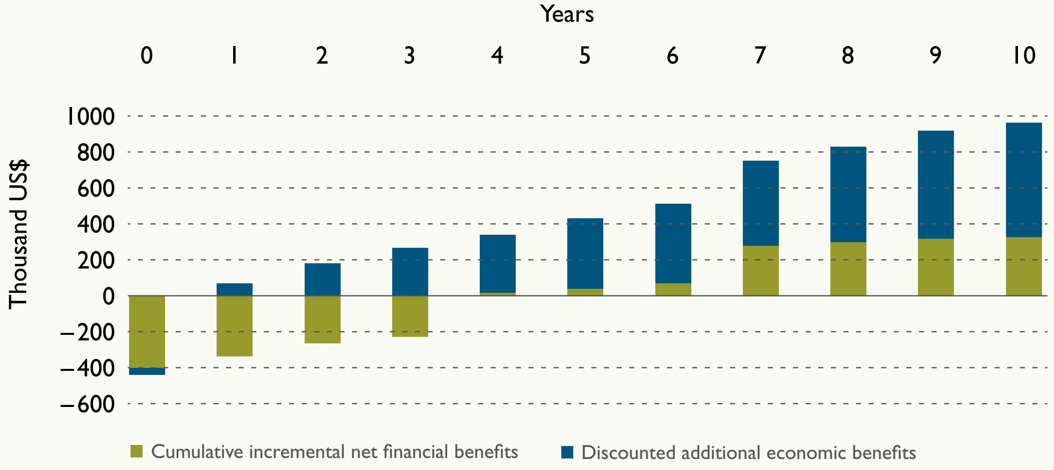
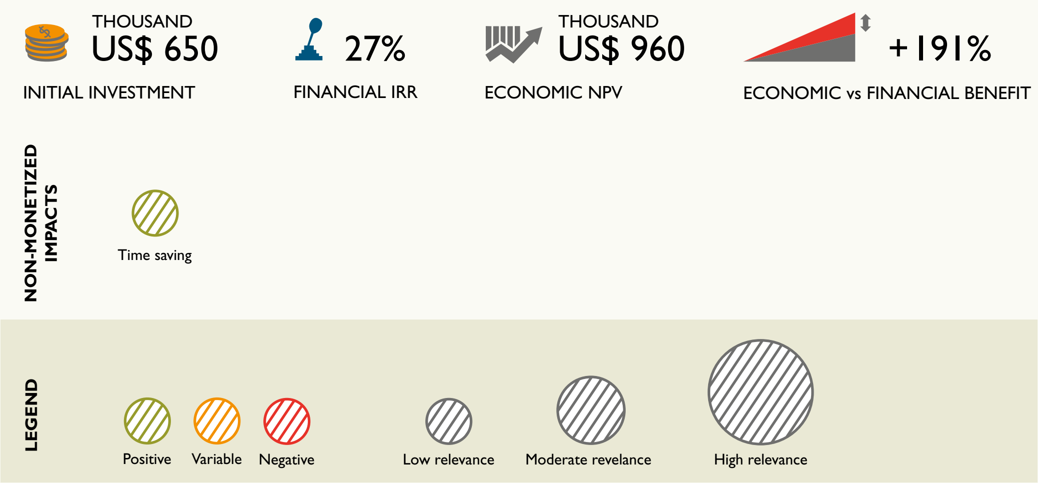


FIGURE 4.36. Key figures of the case study (solar-powered water pump).

Source: Authors.



4.3. RICE VALUE CHAIN

Source: © GIZ/Guenay Ulutunçok

RICE VALUE CHAIN

Milling is a crucial step in processing rice grains after harvest. It removes the husk and the bran layers, producing an edible, white rice kernel that is free of impurities. This process can be carried out either manually at small on-farm scale or mechanically in large rice mills. Mechanized milling operations are far more efficient and less labour-intensive than manual methods.

Milling involves pre-cleaning, removal of husk and bran layers, shelling, polishing, grading, and packaging. Husk and bran removal can be done in a one-step or two-step process where the husk removal is done separately to produce brown rice as an intermediate product. The bran is then removed if white rice is required. Modern commercial rice processing facilities have three basic stages:

(i) Husking
(ii) Whitening-polishing
(iii) Grading

For further details of rice production and processing see Section 4 of FAO and USAID (2015).

4.3.1. RICE HUSK GASIFICATION

Rice husk is commonly considered a waste product of rice processing, sometimes resulting in disposal problems due to the enormous volumes produced. Source: © Land Rover Our Planet via flickr (CC BY-ND 2.0).

The outer husk of the rice grain accounts for around 20 percent of the weigth of produced paddy. The world rice husk output in 2012 was about 120 Mt (Yoon et al., 2012). Rice husk is commonly considered a waste product of rice processing, sometimes resulting in disposal problems due to the enormous volumes produced. In the past, rice millers often simply dumped or burned husk as means of disposal. Alternatively, households can use husks as a solid fuel for cookstoves, ovens or dryers, but burning them results in localized particulate matter (PM) pollution.

Rice husks can be gasified, and the bioenergy in the gases produced can be used for heat and/or electricity generation. Instead of directly combusting the husk to generate heat, gasifiers constrain the air (and hence oxygen) available for complete combustion so that the biomass is converted into a combustible gas (known as producer gas, synthesis gas, or syngas), with a low to medium calorific value. Syngas is a mixture of carbon monoxide, hydrogen, water vapour, carbon dioxide, and methane. Char, tar vapour, and ash particles are also produced.

The fundamental steps in gasification (Figure 4.37) are:

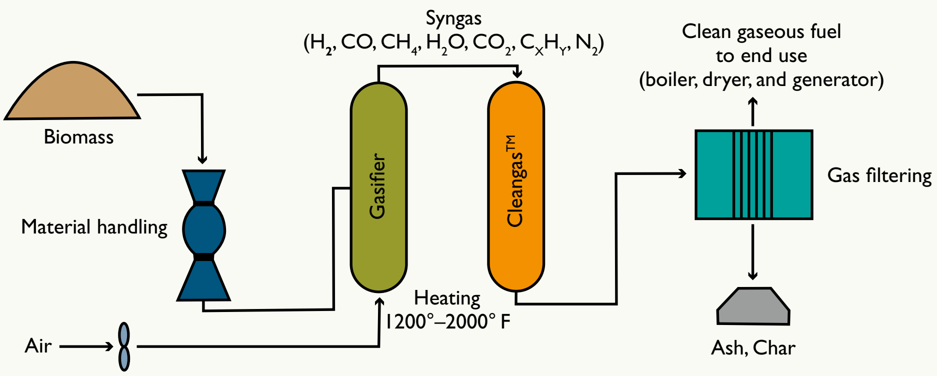
- feedstock preparation, such as shredding, drying and even briquetting the husks;
- gasification, when controlled combustion occurs to produce the syngas; and
- gas clean-up, necessary to remove harmful compounds from the syngas (such as tars or particulates which may clog engines) and to dry the combustible gas.

The gasification process takes place at temperatures higher than 800 °C. For rice husks, the optimal gasification temperature is above 900 °C (Zhao et al., 2009).

Syngas can be cleaned and then potentially substitute natural gas as a fuel for internal combustion engines, industrial heat furnaces, or electricity generation using gas turbines, micro-turbines or fuel cells. When used in gas turbines and fuel cells, higher electrical efficiencies can be achieved than when combusting the biomass and using the heat to produce steam for driving a steam turbine (IRENA, 2012).

FIGURE 4.37. The gasification process to convert biomass such as rice husks to syngas.

Source: adapted from Peterson et al., 2009.

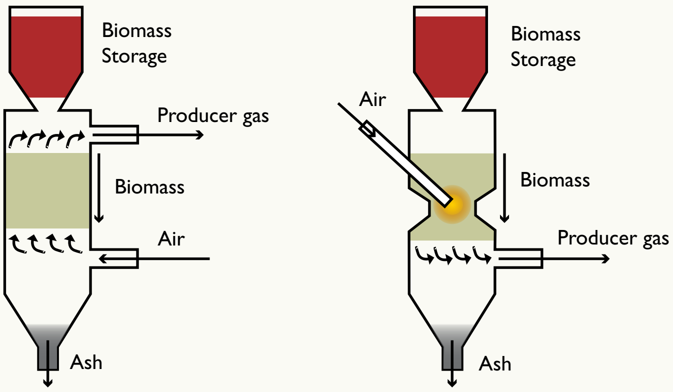


Fixed bed and fluidized bed gasifiers are the main categories of this conversion technology.

In simple, inexpensive, fixed-bed systems, the biomass is piled on top of a grate inside the gasification chamber. It is a proven technology but typically produces gas with a lower heat content. This design is preferred for small- to medium-scale applications with thermal requirements up to 1 MW_{th}. Updraft gasifiers (Figure 4.38) can scale up to as much as 40 MW_{th}, whereas down-draft gasifiers do not scale well beyond 1 MW_{th} (IRENA, 2012).

FIGURE 4.38. Small-scale updraft and downdraft fixed bed gasifier designs.

Source: adapted from IRENA, 2012.



In fluidized-bed gasifiers, the combustible gas is generated by feeding the biomass into a hot bed of suspended, inert material. Generally, it offers improved overall conversion efficiency performance, but with greater complexity and cost. The syngas has a lower tar content but a greater level of particulates as compared to fixed-bed systems (Peterson and Haase, 2009).

Gasification systems can also be classified in close-coupled and two-stage systems:

- In a **close-coupled gasification system,** the combustible gas is burned directly in the gasifier plant and used for space heat or drying, or burned in a boiler to produce steam.

- In a **two-stage gasification system,** tars and particulate matter are first removed from the combustible gas, resulting in a clean gas suitable for use in more demanding applications (Peterson et al., 2009).

When the reactive agent is air-blown, gasifiers are relatively cheap and typically produce a syngas with a high nitrogen content (coming from the air), hence with a low energy content (1.3–1.6 kWh/m^3 on a dry basis). Gasifiers using oxygen or steam as the reactive agent produce a syngas with higher concentrations of CO and H_2 and with a much higher energy content (2.5–5.2 kWh/m^3), albeit at a greater cost than an air-blown gasifier (IRENA, 2012). When combusted, the syngas produces water vapour and carbon dioxide.

Cleaning-up and conditioning of the syngas processes may differ according to the specific pollutant on which it is willing to intervene: cyclone and filters are used for removing bulk particulates; wet scrubbing is used to remove fine particulates, ammonia and chlorides; Solid absorbents are used to remove mercury and traces of heavy metal; water gas shift (WGS) is used to adjust the hydrogen to carbon monoxide ratio; catalytic hydrolysis is used for converting COS (Carbonyl Sulfide) into H_2S; acid gas removal (AGR) is used for extracting sulphur-bearing gases and to remove CO_2 (NETL, 2016). Some of these cleaning procedures can be carried out without the use of water streams and on dry-basis (apart from minor quantities of water needed to refill the system due to evaporation or water leakage). Some others, such as wet scrubbing and water gas shift, need water to clean the technology itself.

Wet scrubbing, in fact, consists of bringing the polluted syngas in contact with a scrubbing liquid in a variety of ways, from spraying the liquid to using a column of streaming liquid in contact with the gaseous fraction. Thereby, particulates are collected in the scrubbing liquid stream/bubbles by absorption gas-liquid. One of the biggest issues related to wet scrubbing, apart from high energy requirements, is the water use and the water disposal problem. In fact, water, after absorbing contaminants, needs to be clarified in sedimentation ponds or with additional sludge clarifiers to be added to the whole system. Water treatment systems can as much as double the total cost of the plant. In addition, if not properly treated, it could generate an additional polluted effluent with associated water pollution and odour. Consequently, wet gasification would have a consistently larger impact both on water resources and in economic terms, compared to dry gasification.

Gasification of rice husks is recommended only for small- to medium-scale utilization (Militar, 2014) since it is hardly competitive with the well-known combustion technology for large-scale applications. Communications with practitioners revealed that gasification can be competitive for smaller systems (50–150 kW) processing up to 1 tonne of rice per hour.

For small-scale and discontinuous power production, it is possible to combine rice husk gasification (RHG) with diesel power generation. Such hybrid diesel-gasification systems have several benefits: Chiefly they avoid the formation of solid tar in the combustion chamber, which is difficult to remove, and allow the system to run for much longer times before cleaning is required, with associated shutdown of the plant. These systems consume around one-third of the diesel that would be needed for a regular diesel generator.

CHP can be applied for heating water or paddy drying as well as producing electricity for milling and/or to sell surplus electricity to the grid. In CHP plants, typically 1 kWh electricity generation requires 2–3 kg of rice husk (FAO and USAID, 2015) – producing also useful heat. In electricity-only plants, 1 kWh is generated from 1.6–1.8 kg of husk (Nguyen and Ha-Duong, 2015).

Husk Power Systems in India claimed that most gasifier units manufactured by the company can generate 32 kWh an hour from 50 kg of husks (equating to around 1.5–1.6 kg husks per kWh). This capacity gasifier can provide the basic needs of a village of about 500 people. Several systems with higher generating capacity exist (IRENA, 2012).

Rice husk ash, a by-product of the gasification process, can be used for a variety of applications such as making green concrete, high performance concrete, refractory bricks, ceramic glaze, insulators, roof shingles, waterproof chemicals, oil spill absorbent, specialty paints, flame retardants, and as a carrier for pesticides (Rice Husk Ash, 2008). The biochar can be used as soil amendment, although the biochar resulting from rice husk has a very low nutrient content.

COSTS

The cost and efficiency of heat and power generation from rice husk energy recovery systems vary significantly by technology, region and plant size. Table 4.29 presents the equipment costs for gasifier technologies by size according to various studies.

TABLE 4.29. Estimated cost for a range of gasification technologies taken from recent studies.

	Study			
Fixed bed gasifier with ICE		4,150	1,730	4,321–5,074
Fixed bed gasifier with GT	3,000–3,500			
Fluidized gasifier with GT			2,470–3,665	
	O'Connor, 2011	Mott MacDonald, 2011	EPA, 2007 and EIA, 2010	Obernberger, 2008

Notes: ICE = internal combustion engine; GT = gas turbine; costs are in 2010 US dollars per kW.

Source: IRENA, 2012.

The total investment cost including gasifier equipment, fuel handling and preparation machinery, engineering and construction costs, as well as planning, ranges between US$2,000–6,000/kW. Thereof almost 60 percent is for the converter system including gasifier, gas collection, and gas cleaning systems (IRENA, 2012).

Communication with practitioners revealed that a 100 kW plant requires an investment of more than US$250,000 capital cost. Such plant would provide access to energy for 200 households in a village off-grid.

Husk Power Systems (HPS) has installed 60 mini-power gasification plants in India for between US$1,000 to 1,500/kW, with an overall conversion efficiency between 4 and 14 percent. These plants are labour intensive and require trained staff for reliable operation and proper maintenance, in part involving tar removal (IRENA, 2012).

O&M costs of a typical biomass power plant range from 1 to 6 percent of the initial capital cost per year. Fixed O&M costs consist of labour, scheduled maintenance, and equipment replacement (such as the gasifier, feedstock handling equipment, etc.), and insurance. Variable O&M depends on the rate of system output and includes alternative fuel costs, ash disposal, unplanned maintenance and repair, component replacement, and incremental servicing costs. Fixed O&M costs range between 3 and 6 percent of the installed cost. The variable O&M cost is taken to be about US$3.7/MWh (IRENA, 2012).

The main labour cost is for biomass handling and logistics as well as feeding the gasifier, requiring a full-time employee. In addition to moving the husks, the cleanliness of all storage sites and equipment needs attention. Managing the biomass gasification facility will also involve labour for tracking biomass purchases, logistics, quality control, and plant emissions documentation. A little less than a half-time position was assessed to be needed to coordinate these activities (Tallaksen et al., 2012).

An estimate has been made of unskilled and skilled labour requirements for a gasification plant according to its capacity (FAO, 2014a) (Table 4.30).

TABLE 4.30. **Number of predicted unskilled and skilled labour units required for a gasification plant according to its electricity generating capacity.**

Unskilled labour	10 kW capacity → 1 person 40 kW capacity → 3 persons 100 kW capacity → 6 persons
Skilled labour	10 kW capacity → 1 person 40 kW capacity → 1 person 100 kW capacity → 2 persons

Source: FAO, 2014a.

Gasification economics are affected by the cost of the rice husk feedstock delivered to the plant, as well as by the lowest-price fossil fuel alternative available (natural gas, propane [LPG], or heating oil). As a reference, in India in 2011, rice husk was priced between US$22 and US$30/tonne (IRENA, 2012).

The biochar resulting from rice husk gasification has no or a low market price as soil amendment, since its nutrition properties are very low compared to other biochars.

MAIN IMPACTS

Gasification of rice husks may be a solution to meet the energy demand of rice mills as an alternative to fossil fuels. It can also provide a solution to off-grid electricity access in rural areas. One litre of diesel fuel can be replaced by gasifying approximately 6 kg of rice husk (Hong Nam et al., 2015).

RHG plants may employ locals to deliver husks to the plant, collect payments for electricity sold, and monitor the electricity usage by customers. They require skilled maintenance, which may not be available locally. Rice husk has low energy density.

Its high silica content makes it very abrasive on equipment and is the reason for special combustion system designs (IRENA, 2012). Silica accounts for 95 percent of the elements in the ash, which can therefore form deposits inside the combustion chamber and gasifier. This slagging and fouling can impair performance and regularly leads to high maintenance costs. Since ash can reach up to 25 percent by weight of rice husk, it can cause damage to the land and the surrounding area if improperly dumped. It can however be sold for use in concrete and block-making to produce added value (IRENA, 2012).

Gasification of husk represents a low-cost energy recovery technology, which can provide a clean energy source for milling operations, while solving the problem of disposal and potentially improving farmers' income where a rice husk market exists.

This technology results in a number of by-products, which include both liquid and solid wastes. Discharging these wastes requires great care. Liquid waste produced by rice husk gasifiers, including wastewater and tar, is produced when cooling and cleaning the syngas. It happens to be discharged into the surrounding environment with little treatment in most cases, with potential metals and other toxic and carcinogenic compounds inside. The tar is generally thrown away or burned although it contains toxic BTEX and PAH compounds at high concentrations. Ways to reuse or destroy tar exist but are highly complex, making tar a problematic by-product of gasification.[77] Gas cleaning requires about 2 litres/kWh of water and can be a major water pollution source (Rice Knowledge Bank, 2016a).

Gasification itself, a bioenergy technology, does not influence the global carbon balance. It also involves lower NOx and particulate emissions compared to direct combustion of biomass. Gasification is a more efficient conversion process when generating power (Peterson et al., 2009). In off-grid areas, substituting electricity for traditional biomass used for cooking or heating can reduce indoor pollution.

TABLE 4.31. Main advantages and disadvantages of rice husk gasification systems.

Advantages	Disadvantages
• Can provide clean energy supply to rice mills. • More energy efficient than direct combustion. • Lower NOx and particulate emissions compared to direct combustion. • Significant reduction of indoor air pollution if replacing traditional biomass. • Improved access to energy in remote rural areas. • Solution to rice husk disposal problems. • Residual ash may find a place in market such as brick industry. • Job creation to maintain and operate the gasifier.	• High maintenance costs and associated labour. • Production of toxic wastewater and tar. • High levels of ash production may affect soil and water. • Noise pollution. • Water needed for gas cleaning (around 2 litres/kWh).

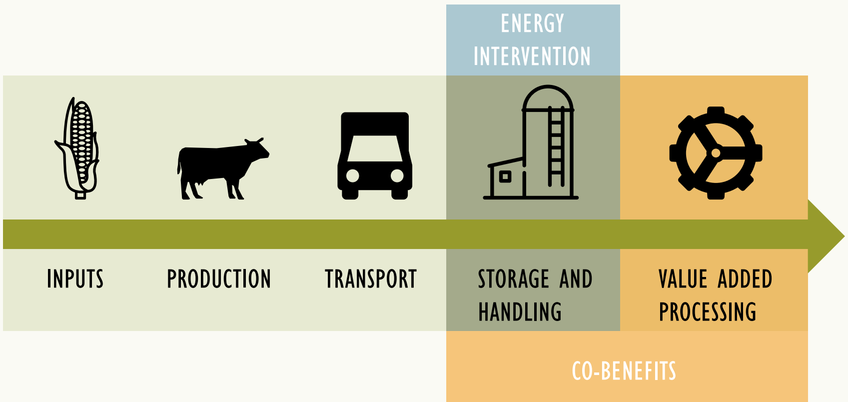
Source: Authors.

77 Hybrid diesel-gasification systems have the main advantage of significantly reducing tar formation (at the expense of diesel fuel consumption).

CASE STUDY: RICE HUSK GASIFICATION IN CAMBODIA

FIGURE 4.39. Location of the intervention and co-benefits of rice husk gasification in the value chain.

Source: Authors.



In 2015, Nexus for Development, a Phnom Penh-based NGO specializing in climate and sustainable project development and financing services, launched together with REEEP a dedicated Revolving Loan Fund in Cambodia. The aim is to provide concessional debt financing to rice millers in the country in order to upgrade their equipment with RHG systems.

The Fund intended on working with SME Renewables, a technical service provider specializing in the design and installation of biomass gasifiers in agricultural and related applications, with a specific focus on rice husk gasifiers. SME Renewables utilized primarily imported gasifiers from the India-based company Ankur Scientific Energy Technologies Pvt. Ltd.

In 2016, the focus on RHG was abandoned after plunges in the price of petrol/diesel deteriorated project economics beyond a point that was considered viable.

Feasibility analysis

Rice has underpinned Cambodia's agricultural sector for thousands of years, and continues to play a central role in the country's economy. In 2012, the agricultural sector provided 26 percent of Cambodia's GDP and 51 percent of total employment (World Bank, 2015b). The agricultural sector – overwhelmingly cropping – is dominated by paddy rice, which makes up around two-thirds of Cambodia's total 3.99 million hectares of cropland.

One key factor, which virtually erases Cambodian millers' potential competitive advantage in paddy prices, is power. Rice millers pay around US$0.20/kWh in Cambodia, around twice as much as their competitors in Vietnam. Electricité du

Cambodia (EDC), Cambodia's state-operated central utility grid, leaves around 75 percent of Cambodians in rural areas without access to the grid (World Bank, 2010). As a result, most millers and farmers rely on diesel or heavy fuel oil (HFO) to power mills, pumps and other equipment, as well as to generate electricity.

These structural deficiencies are exacerbated by a weak financial ecosystem, specifically a combination of insufficient working capital available to actors in the processing sector, and the highly exposed financial position of a large portion of farmers (ADB, 2012, 2012). This has left the sector as a whole highly vulnerable to disruptions in production due to climate-related events such as flooding or drought, or disruptions in price due to other external market factors.

RHG, a technology which on paper is able to provide considerable benefits to the rice-producing sector while reducing greenhouse gas emissions, is hampered in its development by these economic deficiencies. The economics of RHG projects are highly sensitive to volatile commodity prices for inputs as well as outputs (for example, prices of free on board [FOB] rice fell dramatically in 2015) (Hong, 2016), supply chain disruptions, and cash-flow pressures. Ultimately, in 2016, very low diesel prices doomed an already-tenuous business model, extending payback periods for projects from as low as 2–3 years to beyond 10–11 years (see the financial CBA below).

Through a retrofit or new installation of a widely-available dual-fuel RHG system, a rice miller using a diesel or petrol generator to power a mill can reduce the single greatest fixed cost by around 60-70 percent (REEEP Financial CBA; TERI, 2010). With upfront capital expenditures upwards of US$60,000-70,000, the ability to obtain debt financing is critical to the ability of millers to invest in the equipment.

The case study focuses on a hypothetical case informed by early data collection. However, due to drastic falls in the price of diesel and the resulting (in large part) deterioration of RHG project economics at this level, these data were never monitored or verified. This demonstrates the sensitivities of the business model based on generalized market inputs. The prototypical rice miller in this case is operating on a commercial basis and processing approximately 1.5 tonnes/hour, running a single shift of 8 hours/day, 25 days/month, 12 months/year (REEEP/Nexus). This is typical in Cambodia but very low for the region – millers in Thailand, as a comparison, generally run two or three shifts of eight hours per day (World Bank, 2015b). Broadly, a lack of capacity and resilience in the financial system prevents millers from being able to adequately invest in paddy, which in turn results in massive leakages of paddy into neighbouring Vietnam. Increasing the financial capacity of millers – not only to invest in upgrading equipment (including RHG) but also in purchasing paddy – would significantly impact the percentage of the total value of Cambodia's rice being kept within the country. The weakness in the financial system certainly has played a role in limiting investment in RHG, even in a context with high petrol prices.[78]

78 A note on prices: It is difficult to identify the price of rice at various stages of the value chain with a high degree of certainty. Farm gate prices of paddy in Cambodia, for instance, are highly volatile and subject to considerable variation among seasons and regions. This case utilizes a blend of pricing data, with assumptions of "mark-ups" at various stages of the rice value chain to fill in the gaps.

RICE VALUE CHAIN

Description of the energy intervention

SME Renewables is a licensed seller of Ankur Scientific biomass gasification systems.[79] The case study utilizes a FBG-250 machine, which refers to the device's output capacity in kilowatts (250 kW). The FBG-250 consumes up to 300 kg of biomass per hour, which represents about one-third of the typical available husk leftover from milling. The machine is a dual-fuel (or hybrid) diesel-rice husk system, which is able to cut diesel consumption by two-thirds compared to a diesel generator. It allows the gasification system to work discontinuously, limiting the problem of removing solid tar from the combustion chamber.

The gasifier under analysis is offered with a dry gas cleaning system, in which cooling water is not directly exposed to the producer gas and as such can be recycled after cooling and "neutralization". This system is basically phased cooling and filtering. It begins with an (ambient) air-cooling process, followed by rough filtering with bag filters, no-contact water cooling with a couple heat exchangers, a neutralization system for this water, and then fine filtering (a series of sawdust filters and then fabric filters). A dry tar and char by-products are produced, which need to be removed regularly.

Biochar is often discussed as an additive to construction materials (e.g. bricks, tiles, insulators, etc.), or to fertilizers as a soil amendment. Although Ankur provides a dry char discharge system to separate the dry biochar from tar and other liquid by-products, there is no incentive for millers in Cambodia to invest in such system. In most cases, mixed waste is simply deposited in the surrounding environs, including waterways, resulting in unnecessary and potentially hazardous pollution.

Financial CBA

The financial CBA of the project for a rice miller shows a clear long-term benefit in cost savings due to less fuel being required to operate the mill. Because the technology switch does not affect inputs or outputs of the mill per se, the project economics are entirely dependent upon the comparison of fixed and running costs between the two technologies.

Benchmark scenario

A typical rice miller of the level targeted by this technology processes around 3,600 tonnes of paddy per year. About 22 percent of the total weight of paddy is the risk husk, which equals around 792 tonnes of rice husk per year. In Cambodia, millers at this level generally have older machinery and often utilize an inexpensive and/or second-hand diesel generator to provide motive power for the mill machinery (transporters, shakers, threshers, polishers, etc.). The capacity of these engines is often between 74.5 and 261 kW depending on sourcing and engine type. The cost of procuring these engines is approximately US$10,000 (UNFCCC, 2013). Because the lifetime of diesel engines at this load is only around five to six years, millers will need

79 Ankur Scientific, an Indian company that exports worldwide, offers three types of technology according to the type of biomass used as an input and its moisture content: a wet-basis gasifier (WBG) for firewood, wood waste, coconut shells or other wood-like biomass; a fine-based gasifier (FBG), for fine biomass such as rice husks; and a combination system that allows both high moisture content and fine biomass to be used as fuel.

to invest in an engine twice over a ten-year period (the expected lifetime of the RHG system).

The financial CBA includes assumptions regarding the average calorific values of rice husk and diesel fuel in the field; the efficiency of the dual-fuel generator; the average lifetime of diesel motors in the field; the prices of husk and paddy, as well as the typical average mark-ups over farm gate paddy price that occur throughout the rice value chain (Table 4.33). The per tonne price of rice or its progression through the value chain has no impact on the model.[80]

The following assumptions were made in the CBA:

- **Interest rate:** The model assumes a discount rate of 14 percent over the project lifetime, which has been used by development finance institutions in similar project financing cases in the country (PFAN, 2015).

- **Life expectancy of the technology:** The expected lifetime of the RHG system is 10 years.

- **Scale:** The FHG-250 can easily process 3,600 tonnes/year of paddy under the existing model. However, because Cambodian mills typically operate under capacity compared to mills in neighbouring countries, there is no physical impediment for a mill scaling from one or two to three eight-hour shifts per day, which would drastically improve the overall performance of the sector in Cambodia (IFC, 2015).

Costs

Capital costs: The FHG-250 was offered by SME Renewables for a total estimated cost of around US$76,000. This figure includes US$65,000 for turn-key costs of the equipment (with import duties), US$8,000 for civil works, and US$3,000 for miscellaneous related costs of the machinery upgrade.

Operating and maintenance costs: Fixed costs of running the RHG system are dramatically lower than those of diesel due to the decrease in fuel expenditures, which range from US$26,000 (using December 2015 prices) to US$50,000 annually (using January 2015 prices).

Maintenance costs are higher for the RHG than for the basic diesel-powered milling, demanding increased labour to clean the system and dispose by-products, as well as filters and additional maintenance equipment. The case study estimates that two additional persons required to run and maintain the RHG system at a cost of US$300/month.

80 The model has assumed a 30/70 split of fragrant to mixed rice (World Bank, 2015b).

Benefits

As mentioned above, no additional income results from the project investment, as processing volumes and outputs remain the same. Were millers able to invest more strategically in obtaining and storing paddy, the benefits of the RHG would be greater. Adding an eight-hour shift would double processing capacity and output, which would off-set the negative effects of low diesel prices, returning the investment to viability.

Financial profitability

The financial CBA of the RHG is strongly dependent on the price of fuel and the system capacity. In the table and figures below, the differences in the financial NPV of the three project scenarios (with the price of diesel from January 2016 and by adding an eight-hour shift to double processing capacity) are visible.

TABLE 4.32. Financial CBA of rice husk gasification compared with benchmark.

		Unit	RHG	Diesel mill	Notes
Life expectancy of the technology		year	10	12,000 h (approx. 5y)	
Financial costs					
Capital cost		Thousand US$	76	10	ANKUR gasifiers with dry ash removal, wet gas filter technology
Labour costs		Thousand US$/year	8.4	4.8	UNFCC, 2013; REEEP, 2015b
Fuel costs		Thousand US$/year	8.7–16.3	26.4–50.0	2/3 reduction (REEEP, 2015b)
Maintenance and repair		Thousand US$/year	13.1	9.9	UNFCC, 2013; REEEP, 2015b
Financial benefits					
Revenues from rice		Thousand US$/year	1,333	1,341	Price of rice husk: US$17/tonne
Financial profitability indicators					
Scenario 1: diesel price S$0.55/litre	NPV	Thousand US$	–43.8		
	IRR	%	–8		
Scenario 2: diesel price S$1.03/litre	NPV	Thousand US$	47.5		
	IRR	%	30		
Scenario 3: operating two 8h processing shifts	NPV	Thousand US$	60.8		
	IRR	%	34		

FIGURE 4.40. Cumulative discounted net financial benefits over ten years: Scenario 1 (rice husk gasification).

Note: This scenario uses diesel prices from December 2015 at US$0.55/litre.

Source: Authors.

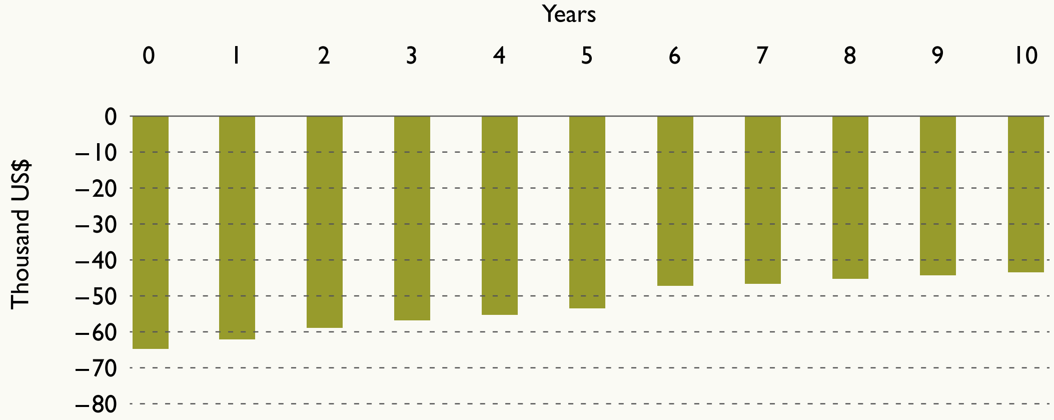
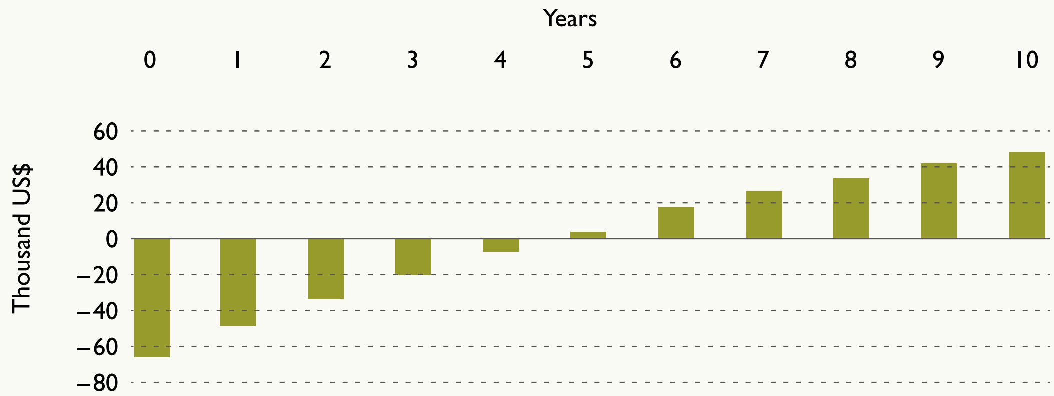


FIGURE 4.41. Cumulative discounted net financial benefits over ten years: Scenario 2 (rice husk gasification).

Note: This scenario uses diesel prices from January 2016 at US$1.03/litre.

Source: Authors.



Economic CBA

Value added along the value chain

Nearly one-quarter of the total profit of rice production occurs after the milling process (ADB, 2012). Based on the Asian Development Bank's value chain marketing mark-up estimates, one tonne of milled rice would yield approximately US$116 in value chain profit. However, since the energy intervention does not result in a change in volume or quality of rice processed, there is no impact at subsequent stages of the value chain.

FIGURE 4.42. Cumulative discounted net financial benefits over ten years: Scenario 3 (rice husk gasification).

Note: This scenario uses diesel prices from December 2015 at US$0.55/litre for a mill operating two 8-hour processing shifts.

Source: Authors.

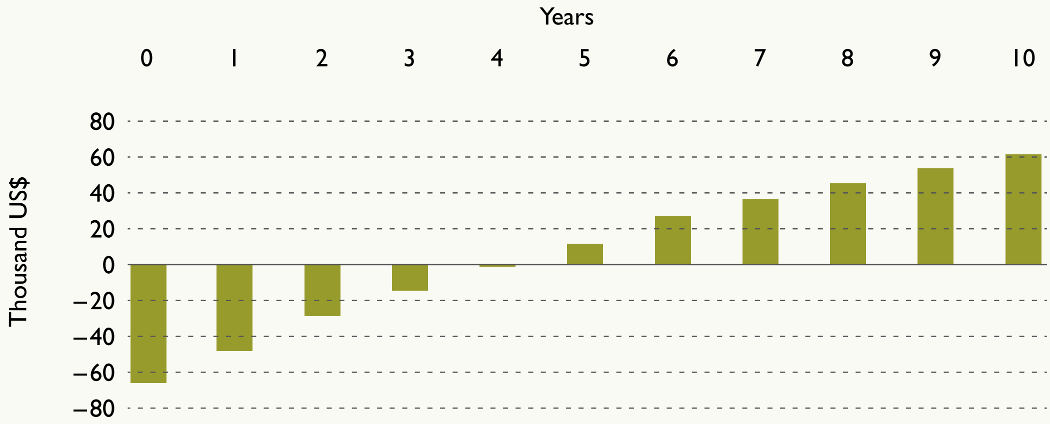


TABLE 4.33. Marketing costs and margins for rice, 2006.

	Input	Farmer	Collector	Miller	Transporter	Wholesaler	Retailer	Total
Transport cost			20		60	10.00		
Operating cost			5	49.64		6.00		
Input cost		255.97	500.00	530.00	675.84	750.00	832.00	
Total cost		256	525	579.64	735.84	766.03	832.00	
Price received	255.97	500.00	530.00	675.84	750.00	832.00	896.00	
Value of by-product		16.13		117.57				
Total revenue	257.97	516.13	530.00	793.41	750.00	832.00	896.00	
Profit	256	260	5.0	213.8	14.2	66.0	64.0	623.06
		50.4%	0.94%	26.9%	1.9%	7.9%	7.1%	
% of total profit		42	0.80	34	2	11	10	100
Marketing margins		**29.04**	**3.35**	**16.28**	**8.28**	**9.15**	**7.14**	
Mark-up over farm gate price (%)	**28.57**	**3**	**6.0**	**59**	**50**	**66**	**79**	**42.40**

Note: 3 tonne/ha yield, transport from Battambang to Phnom Penh Riel per kg of paddy rice, milling recovery 0.64.

Source: ADB, 2012.

Subsidies and taxes

In March 2016, the Cambodian government instituted a blanket exemption from the country's 10 percent for rice products and milling machinery, which includes RHG (Sothear, 2016b). There is thus no effective change in government tax revenue for VAT.

Imported machinery is subject to a 15 percent import tax (General Department of Customs and Excise of Cambodia, 2016), which is included in the project capital expenditures figure in the financial CBA. Here it represents an additional gain for the government from importing the RHG equipment.

The government revenue as a result of export certification amounts to approximately US$14/tonne and remains unchanged in the economic CBA (Table 4.34).

TABLE 4.34. Rice export procedures and certification costs.

Rice export procedure / certification	Amount	Unit
SPS certificate	35	US$/case
Fumigation certificate	35	US$/container
Certificate of origin	141	US$/case
Custom certificate	6	US$/container
CamControl certificate	52	US$/container
GMO certificate	80	US$/sample
Avg. total	**14**	**US$/tonne**

Source: World Bank, 2015a.

Finally, the introduction of RHG technology reduces tax revenue from fuel. Diesel is taxed at a flat rate of 4.35 percent (PWC, 2015). This amounts to currently US$0.02/litre at a diesel price of US$0.55/litre.

Assessment of environmental and socio-economic impacts

There is little information to support a quantitative analysis of the costs and benefits of the technology in terms of local environmental impacts. However, there is, as of today, a clear negative impact on the local environment due to improper disposal of gasification by-products. Were the by-products of the RHG process to be disposed of or used optimally, the project would potentially result in negligible environmental impacts, while also providing positive economic benefits through the application of biochar as a materials additive and/or soil amendment.

Soil quality

Waste disposal areas at Cambodian RHG installations are heavily polluted, resulting in visible and olfactible deposits of "ash, black water, tar, and char" (Nguyen et al., 2015). The energy intervention generates an observed but non-quantifiable environmental damage due to uncontrolled disposal of RHG by-products.[81]

81 However, under optimal conditions, the technology could improve soil quality through the application of biochar as a materials additive and/or soil amendment. These conditions are not met in the Cambodian case study.

Impact	Relevance
Negative	High

Fertilizer use and efficiency

Gasification by-products could potentially reduce the need of fertilizers if properly processed and applied to the soil. However, in this case study these benefits are unrealized.

Impact	Relevance
No impact	–

Indoor air pollution

Impact	Relevance
No impact	–

Water use and efficiency

For a gasification system comprising a dry system for gas cleaning (dry gasification), water is only needed to cool the system. This water is not exposed to the producer gas (as in the case of wet scrubbing of flue gases) and as such can be recycled. There are minor water losses due to evaporation.

Impact	Relevance
Negative	Low

Water quality

Since the only freshwater used is needed to compensate water loss due to evaporation, the impact on water quality from effluents (e.g. leaked water or water used to clean the equipment) is negligible.

The situation would be significantly different if a wet scrubber was used to treat the flue gases. In this case, the impact would be major and wastewater would need to be treated properly. If not properly treated in a treatment plant, wastewater of wet gasification plants is discharged into the surrounding environment, with subsequent environmental pollution due to metals and other toxic and carcinogenic compounds (relevant negative impact on water quality).

Impact	Relevance
Negligible	–

Food loss

Impact	Relevance
No impact	–

Land requirement

A 250 kW rice husk gasification plant occupies an area typically of 50–100 m^2. This land is usually non-productive (the plant is usually built close to the miller, which is generally non-agricultural land). The impact in terms of requirement of productive land can therefore be considered negligible.

Impact	Relevance
Negligible	–

GHG emissions

At the 19th Conference of the Parties in Warsaw, Poland, the UNFCCC adopted a Clean Development Mechanism standardized baseline from Cambodia's Environment Ministry for "Technology switch in the rice mill sector of Cambodia". This includes both the existing diesel-powered rice processing machinery as well as the dual-mode RHG-diesel systems. The standardized baseline did not include the measure of methane avoidance which may occur through the decay of rice husks under anaerobic conditions (UNFCCC, 2013).

Technology 1 of the baseline, diesel-powered milling machinery, has an emission factor of 0.051 tCO_2/tonne of rice, whereas Technology 3, the dual-mode RHG-diesel generator, has an emission factor of 0.0162 tCO_2/tonne of rice (UNFCCC, 2013).

For the purposes of this case study, the EPA estimate of the "social cost" of carbon, valued at US$36/tonne of CO_2, is used (EPA, 2016). At this valuation, a diesel-powered rice mill with a processing capacity of 1.5 tonne/hour (this case) is responsible for US$6,558 in "carbon damage" annually. A RHG system by comparison is responsible for US$2,100 in carbon damages – a difference of US$4,458 annually.

Impact	Relevance
Positive	High

Access to energy

Impact	Relevance
No impact	–

Household Income

Impact	Relevance
No impact	–

Time saving

Impact	Relevance
No impact	–

Employment

There is an increase in employment wages based on the expected two additional staff needed to operate, clean and maintain the RHG system, calculated at US$3,600/year. Since this is the market value of the employment generated in the local economy, the full amount is credited to the economic CBA.

Impact	Relevance
Positive	Moderate

TABLE 4.35. Summary of environmental and socio-economic impact (rice husk gasification).

	Indicator	Impact
Environmental impacts	Soil quality	Negative
	Fertilizer use and efficiency	No impact
	Indoor air pollution	No impact
	Water use and efficiency	Negative
	Water quality	Negligible
	Food loss	No impact
	Land requirement	US$4,458 per year
	GHG emissions	No impact
Socio-economic impact	Access to energy	No impact
	Household income	No impact
	Time saving	US$3,600 per year
	Employment	US$70/year (1 new job for every 30 pumps sold)

Note: green = positive impact, yellow = variable impact, red = negative impact.

Source: Authors.

Assessment of economic profitability

Table 4.36 summarizes the monetized economic, environmental and socio-economic impacts of the case study. Even with a diesel price at US$0.55/litre, the economic NPV is positive (US$7,963) and, from an economic perspective, the investment pays back in about 7–8 years.

TABLE 4.36. Economic CBA of the case study: Scenario 1 (rice husk gasification).

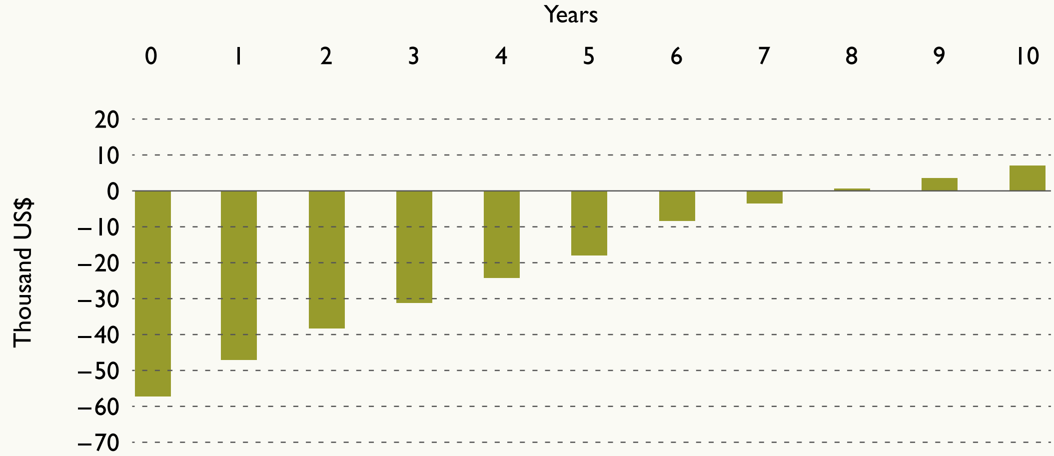
	Unit	RHG	Diesel mill	Notes
Economic benefits				
Value added down the value chain	US$/year	419,784	419,784	US$116/tonne
Import duty	US$	8,478	0	15% import tax
Export certifications and processing	US$/year	32,256	32,256	US$14/tonne
Tax revenue from fuel	US$/year	363	1,101	4.35% tax

Environmental and socio-economic benefits				
GHG emission reduction	US$/year	2,100	6,558	
Employment creation	US$/year	8,400	4,800	2 additional staff
Economic profitability indicators				
NPV (diesel price US$0.55/litre)	US$	7,963		
IRR (diesel price US$0.55/litre)	%	17		

Source: Authors.

FIGURE 4.43. Cumulative discounted net economic benefits over ten years: Scenario 1 (rice husk gasification).

Source: Authors.



Results

Based largely on the climate benefits of reduced carbon emissions, the total economic CBA yields a positive net present value of US$7,963 and a 17 percent IRR, even at current low diesel prices. Using diesel prices from January 2015, the project results in a much higher economic NPV of US$95,469 and an IRR of 48 percent.

As mentioned earlier in the section, the biochar – the primary by-product of RHG – could hypothetically add value to the investment by serving as a low-cost additive to construction materials, or as a soil amendment in the form of fertilizer (Shakley et al., 2011). In practice, however, the biochar is not adequately separated from the process' other by-products (tar, residual metals, and other organic and inorganic contaminants).

Reportedly, waste disposal areas at Cambodian RHG installations are heavily polluted (Nguyen et al., 2015). It is thus more likely, under current practices, that the waste by-products contribute negatively to the total value assessed. Due to a lack of data on such impacts, however, they cannot be reliably quantified or monetized.

FIGURE 4.44. Cumulative discounted net financial and economic benefits over 10 years of the rice husk gasification technology (rice husk gasification).

Source: Authors.

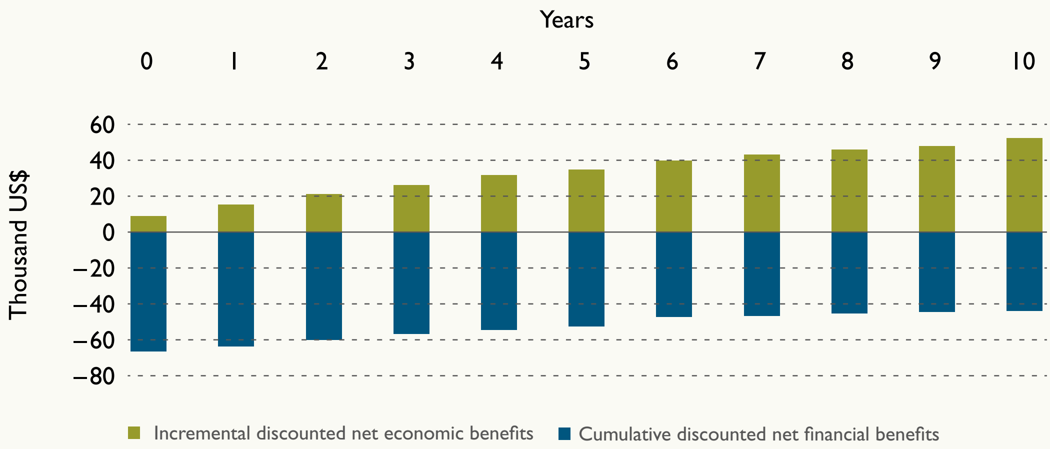
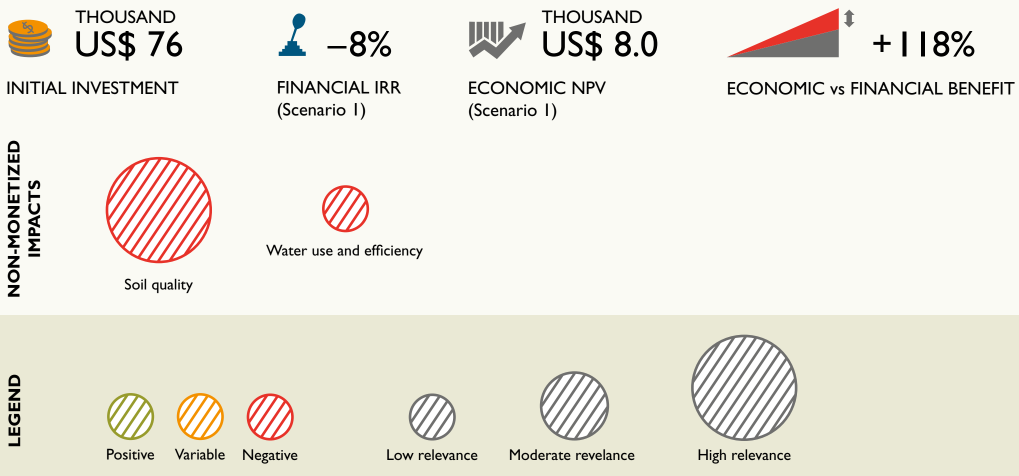


FIGURE 4.45. Key figures of the case study (rice husk gasification).

Source: Authors.



4.3.2. SOLAR-POWERED DOMESTIC RICE PROCESSING

Solar-powered rice processing can substantially reduce the time and energy spent on milling. At the same time it increases productivity, time available for other productive activities, and income for women farmers and their families.
Source: © Agsol/Matt Carr.

Small-scale rice processing machines, such as a rice husker for separating the husk from the grain (Figure 4.46) or a rice polisher to remove bran particles from the rice kernels, can be powered by electricity, using various energy sources, including generating sets powered by diesel engines. Many small rural villages and towns cannot afford a diesel genset or are off-grid, so they have limited or no access to reliable sources of electricity. They rely on manual processing of rice, use belt-drive equipment powered by a diesel engine and belt pulley, or have to travel long distances to an existing large-scale rice mill. They can spend as much on transport to and from a mill as on rice processing fees (IRENA, 2014).

FIGURE 4.46. Examples of a small-scale rice husker and rice polisher.

Source: screenshots with kind permission taken from democlip on solar powered agro-processing machines developed by Agsol (https://www.youtube.com/watch?v=xWgevfqIvdU)

While manual processing is usually undertaken by women and children, diesel-powered mills are generally operated by men (IRENA, 2014).

In a typical small- to medium-sized operation, the milling activities consume a large share of total electrical demand. In Bangladesh for example, a husker consumes about 18.8 kWh/tonne while for modern milling, includes husking, polishing and grading, the energy demand is 29.16 kWh/tonne (FAO and USAID, 2015).

TABLE 4.37. Energy demand of rice processing.

System/method	Energy demand	
	Raw rice	Parboiled rice
Husker	144.0 MJ/tonne (40.0 KWh)	164 MJ/tonne (45.6 KWh)
Sheller	108.0 MJ/tonne (30.0 KWh)	123 MJ/tonne (34.2 KWh)
Modern rice mill	79.2 MJ/tonne (22 KWh)	90 MJ/tonne (25.0 KWh)

Source: Adapted from Goyal et al., 2012.

A typical centrally located, diesel-powered rice mill can process rice 50–100 times faster than manual methods. The average capacity of around 2 kW exceeds the needs of scattered rural settlements. When the raw rice is transported to the mill, such mill can serve the milling demand from 50–100 households/hour of use, with a significantly higher demand during the harvest season (IRENA, 2014).

Solar-powered rice processing is usually driven by a DC motor powered by solar PV modules connected directly to a milling system component such as a husker or polisher. The system consists of solar PV modules, a holder frame, batteries, electrical cables, a charge controller and the milling components with uncorporated electric motors. Alternatively, the mill can be driven by an AC motor. In this case an inverter is needed to transform DC (from the PV system) to AC. This additional component contributes to the rise of the PV system cost and decreases the overall energy efficiency of the system (typically between 10 and 15 percent).

Small mills suitable for a village typically require 150–350 W of solar power capacity and can process 10–50 kg of raw rice per hour. As an example, a small 375 W mill can process 40 kg/h or 400–500 kg/week (8–10 bags) if run for 2 hours/day, so it can serve 40–80 households (FAO and USAID, 2015). Larger commercial-scale mills require 1.1–2.2 kW power to process 100–500 kg/h (IRENA, 2014).

Solar PV systems can be accurately sized according to mill capacity. Lower capacity mills are suitable for installation in smaller settlements (FAO and USAID, 2015). For small mills, the solar panel power required for each hour of use is 80–200 W, and 500–1,000 W for larger mills (IRENA, 2014).

The energy requirements and processing rate of the rice husking by manual, diesel or solar systems are compared in Table 4.38.

TABLE 4.38. Energy requirements and processing rate of rice husking using manual, diesel or solar-powered systems.

Rice husking	Manual	Diesel	Solar	
			Small-scale	Larger-scale
Technology	Mortar and pestle	Diesel-powered belt-drive husker	PV-powered electric	
Mill processing rate	2–5 kg/h	100–200 kg/h	20 kg/h	100 kg/h
Mill power required	–	2–3 kW and above	0.35 kW for mill (PV panel power: 160 W)	1.1 kW for mill (PV panel power: 500 W)

Source: IRENA, 2014.

While both AC and DC motors serve the same function of converting electrical energy into mechanical energy, they are powered, constructed and controlled differently.[82] Usually, DC motors use brushes (although brushless motors also exist) and a commutator, which requires maintenance and reduces the life expectancy. Conversely, AC induction motors do not use brushes, always require an inverter, are more rugged and have longer life expectancies (Ohio, 2016). An advantage of the DC motor is that electricity produced by the panels can be fed directly to the motor during sunshine, with no additional losses or battery maintenance, thus minimizing maintenance costs (Solar Milling, 2012).

Batteries can store solar energy to power the mill at night or on a cloudy day. In a battery-free direct drive system, the solar power capacity needs to at least cover the mill power demand. However, batteries are expensive and have a short life, so they are not an optimal solution unless milling is usually not undertaken in daytime (IRENA, 2014).

In DC systems, it is important to protect the battery against surge currents (when battery is discharged and the voltage low). One possible solution is the use of a relay to control a (low power) circuit running through a switch that is controlled by the operator, coupled with a solar regulator.[83]

COSTS

The benchmark option of a diesel rice mill of 200 kg/hour capacity costs around US$3,000 but has a fuel operating cost of US$1–3/day (depending on oil price), or around US$500–1,000/year; even more when mills are run more than 1 hour/day. In contrast, a 40–80 kg/hour solar rice mill may also be installed for around US$3,000 with zero operational (fuel) costs but a lower processing capacity.[84] A smaller PV-powered solar rice mill system with battery and inverter can cost around US$1,150–1,800 (FAO and USAID, 2015).

82 For example, Village Infrastructure Angels (VIA) and their partner Project Support Services developed machines powered by 24V DC motors (PAEGC, 2016a). Solar Milling, instead, designed a Solar PV Grain Mill that works with an efficient 3-phase AC motor which is directly coupled to the graining system (Solar Milling, 2012).

83 If the regulator senses low voltage of the batteries, it cuts the control circuit to the relay, which then cuts the high power circuit to the machine.

84 While this mill may be two to three times slower, it is appropriately sized for a village of 40–80 households. Most diesel mills are over-sized for their application, and some have been installed for political rather than technical reasons.

At US$1/W capital cost and 1,500 hours of productive power demand per year, the cost of energy from solar is approximately US$0.07/kWh over 10 years, or US$0.14/kWh over 5 years. For example, with diesel at US$1/litre, a genset with 3 kWh/litre output efficiency has a generation cost of US$0.33/kWh. Even with higher installed costs per watt, the payback period of solar displacing diesel is attractive (IRENA, 2014).

Brushed DC motors need replacing every 500–2,000 hours and are about one-half of the price of brushless motors (and easier to source in smaller quantities).

For DC systems, surge currents are drawn directly from the battery. Hence, motors are more expensive than AC motors of similar output. However, the extra cost is probably lower than the cost of adding more PV panels and an over-sized inverter to accommodate the start-up load.

MAIN IMPACTS

The advantages of a PV-powered rice mill (Table 4.39) are the possibility to be operated off-grid and to be widely useable whenever and wherever the solar resource is available. Access to energy services can be given to those remote villages without grid connections that are too far from commercial-scale mills and for whom it is too costly to transport the rice (FAO and USAID, 2015).

Since women usually undertake the arduous task of manual milling using a mortar and pestle, introducing mechanical milling may greatly ease their workload. If solar-powered, mills are also more user-friendly since they are easier to operate than diesel-powered mills (IRENA, 2014).

Reducing the time and energy spent on milling could increase the time available for other productive activities, and increase productivity and income for women farmers and their families (PAEGC, 2016a).

Solar power involves no GHG emissions. The production of components such as batteries and solar panels contribute to GHG emissions from a life cycle assessment (LCA) perspective but these are usually small compared with the manufacturing of a diesel engine and emissions from fuel combustion.

A disadvantage of PV-powered rice mills is their high capital costs, often prohibitive for the rural poor without appropriate financial support. For the same capital cost, diesel-engine driven mills have a greater capacity and higher output than solar mills.

In addition, a DC motor involves relatively high start-up currents requiring a start-up resistor which may break easily. The start-up current also means that the load (such as the rice processing components) cannot be directly connected to the charge controller, but must be connected to the battery, which is therefore not protected against deep discharge. Users must be trained to switch off the mill as soon as the charge controller indicates a deep discharge. This problem could be solved by including a shunt governed by the load contact of the charge controller. The shunt disconnects the mill as soon as it switches off the load (WISIONS, 2014b).

The technology requires skilled technicians for support services during installation and for maintenance.

TABLE 4.39. Main advantages and disadvantages of solar-powered domestic rice processing systems.

Advantages	Disadvantages
• Sizeable to match specific power demand. • Reduction of women's workload. • Avoidance of travel time and costs to central mills which can improve incomes when extra time is spent for other productive activities. • Reduced fossil fuel consumption. • No GHG emissions during operation. • Indirect employment creation.	• Lower productivity than diesel-engine system of similar cost. • Higher start-up and maintenance costs. • Know-how needed. • Smaller units need more skilled operators.

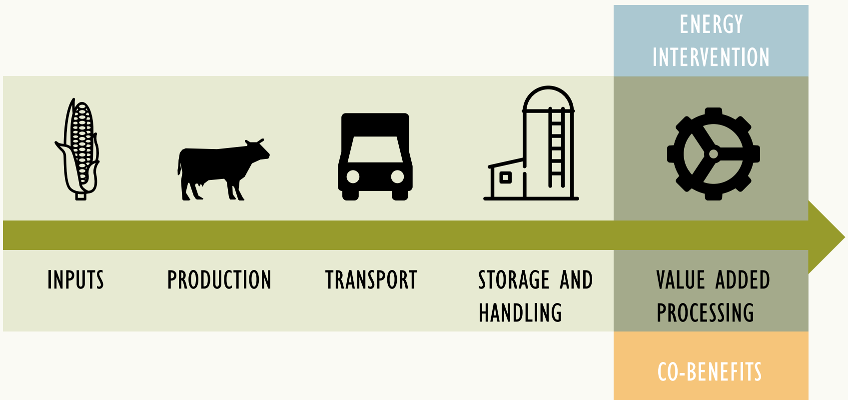
Note: Compared with a diesel-powered belt-drive system as benchmark.

Source: Authors.

CASE STUDY: SOLAR-POWERED DOMESTIC RICE PROCESSING IN PAPUA NEW GUINEA

FIGURE 4.47. Location of the intervention and co-benefits of solar-powered domestic rice processing in the value chain.

Source: Authors.



This case study is based on solar-powered domestic rice millers introduced in Papua New Guinea by Village Infrastructure Angels (VIA). VIA provides solar-powered agro-processing facilities in Indonesia, Papua New Guinea (PNG), Philippines, and Vanuatu. Project finance over one to 3 years can remove the upfront cost barrier, and aims to demonstrate that 70–100 percent of households can afford properly financed infrastructure leading to ownership, while also delivering a commercial return on capital to investors. The company aims to mobilize investor capital for US$10–20 million to assist 10,000 households to gain access to electricity, including risk guarantees and grants to absorb early stage learning and defaults.

In 2014, IRENA contracted VIA to undertake a project to build the capacity of entrepreneurs in Vanuatu and Papua New Guinea so they could design, build and operate at least two solar-powered village-scale rice processing mills, evaluate the impacts, and disseminate the findings via local workshops for stakeholders (IRENA, 2014). IRENA also supported capacity building activities to eliminate diesel drives and manual labour in 50 households.

The selected supplier was Agsol, which develops solar-powered agro-processing machines in China.

Feasibility analysis

The Pacific Islands face large import bills for diesel and gasoline for small generators, and for kerosene to provide lighting in many off-grid villages. PNG, with electrification rates of only 12 percent, is particularly dependable on fossil fuel supply. Replacing fossil fuel imports with local renewable energy can reduce this vulnerability drastically.

A typical rural village in PNG is around 30–50 households, but diesel mills are only suitable for larger villages with 100–300 household. In remote areas, diesel mills of 2–3 kW capacity are generally over-sized for the market. They can process 150–250 kg/h of rice but serve fewer than 100 households/day with a much lower demand. Many diesel mills in PNG are over-sized since they are often installed to gain local votes by politicians (IRENA, 2014).

In many rural villages, a "power gap" can be found between the maximum power a villager can use for manual processing of rice (100–200 W) and the minimum size of a diesel-powered mill (around 2 kW). This provides an opportunity for small (200–750 W) and medium (750 W–2 kW) options that can better serve the needs of 5–15 households or 15–50 households, respectively. Small, low capacity (20–50 kg/hour), highly-utilized rice mills are fit for 50 households or less. Solar milling allows small villages to have their own facility, thereby saving on manual labour and avoiding travel costs to a commercial mill nearby (IRENA, 2014).

IRENA (2014) estimated that 2,000 small off-grid diesel mills are sold annually in the Pacific at a market value of US$4 million/year. However, even more solar mill units could be sold since their smaller capacity meets the market demand for milling.

Description of the energy intervention

This analysis focuses on the combination of two commercial Agsol rice technologies: a rice husker using rubber rollers, and a polisher. The solar-powered rice processing technologies selected by VIA (Table 4.40 and Figure 4.48) rely on a DC motor with brushes. They are equipped with a small inverter to convert DC power to run small

AC appliances. Since heavy short rain bursts or cloud cover are common in the South Pacific region, and small interruptions in solar resources would cause direct-drive mills to stop, the system is also equipped with a battery backup (30 minutes of operation).

TABLE 4.40. Solar-powered domestic rice processing technologies as commercialized by VIA.

	A 0.5 kW drive triple rubber roller brown rice mill that undertakes husking and winnowing of the grain to separate it.
	A 0.75 kW steel worm-fed white rice mill that husks, winnows, and polishes the raw rice.

Source: adapted from IRENA 2014

FIGURE 4.48. Solar-powered electric motor driven rice husking mills.

Source: Agsol.

A 12V battery of 20–40 amperhours (Ah) capacity supplies "cold cranking amps" to start the mill and provides 30 minutes of running time for a 180–500 W mill. An adaptor box enables a customer to plug the machine into any standard 24V DC system.

Solar PV systems of 0.5 kW_p require 40 amperes (A) of current to drive the mills. For one hour of operation, 20–40 Ah of energy is required. PNG generally has 4–5 sunshine hours per day, so 5–10 A minimum from the solar panels is needed to recharge the battery.

Since the system is also intended to power small AC appliances, a 0.75–2.5 kW inverter is recommended for 150–500 W mills with a cost of US$50–500. For this analysis, US$0.20/W was adopted for inverters. The system is equipped with a relay to provide low voltage protection to the battery.

The system requires 25 Wh of electricity per kg of white rice and has a productivity of about 120 kg/day.

Financial CBA

Benchmark scenario

Most households undertake rice processing manually or pay for services from a local (community) mill powered from the central electricity grid or diesel. Most off-grid communities use diesel engines to directly drive belt-driven equipment villages. The local mill is belt-driven by a diesel engine, electricity is not produced. Therefore, a 2 kW diesel mill with a processing rate of 100 kg rice/hour to service 100 households was adopted as a benchmark (Figure 4.49).

Most small mills in PNG use modified Engelberg huskers, which have high grain losses and breakage. It is assumed that a 2.2 kW diesel would be the smallest engine readily available. Such engine would consume 0.5 litres of diesel for processing 50 kg/day – to be comparable with the solar mill. About 1,000 hours of operation was assumed for the diesel engine operating for 1–2 hours/day, 5–6 days/week, giving it a 2–4 year lifespan.

Since villagers do not own the diesel mill, they pay a service fee to process their rice. The typical cost of milling is around US$0.025–0.035/kg (IRENA, 2014), so processing 50 kg of rice would cost a household about US$1.5. Assuming the diesel mill is located an average 5 km away from local village, farmers may take 1 hour using free transport, or it may cost US$1–2 for a return trip using motorized transport. Assuming that households from a remote village have to make about 100–150 trips to the big mill every year (to mill about 200 kg each time), the cost of transport is almost equal to the milling cost. Moreover, diesel engines show high failure rates in rural areas due to poor maintenance, low access to specialized technicians, unavailability of parts and low quality fuel – which is often contaminated from poor handling practices by the time it gets to rural areas (Pers. comm. Agsol, 2016). The diesel mill's frequent breakage and damage represent a risk for farmers from the small villages, who often spend time and money to reach the mill to find it out-of-order.

It is assumed that a village of 50 households in PNG can have an average production of 26 tonnes/year of paddy rice, since in PNG there is normally one harvest per year with an average yield of 2.6 tonnes/ha (FAOSTAT, 2016). Processing this rice at a diesel mill with a capacity of 100 kg/h takes about 260 hours/year. We assume an opportunity cost for this time spent at the mill equal to the average wage for agricultural services in PNG. This is considered to be equal to the minimum wage of PNG kina (PNK) 3.20/h in 2014 (around US$1/h) (United States Department of State, 2015).

The following assumptions were made in the CBA:

- **Interest rate:** The ten-year government bond interest rate as reported by the Bank of Papua New Guinea (BPNG) averaged 8.21 percent from 2001 until 2016. The Central Bank discount rate was 14 percent on 31 December 2010 but 6.92 percent on 31 December 2009 (CIA World Factbook, 2015). The 182-day Treasury bill interest rate between 2011 and 2016 grew from 4.3 to 7 percent (IMF, 2015). The interest rate in Papua New Guinea was thus assumed to be 10 percent.

- **Exchange rate:** The PNG kina has depreciated by 16 percent vis-à-vis the U.S. dollar since June 2014, when BPNG brought the market rates within a trading band around the official rate (IMF, 2015). PGK 1 was assumed to equal US$0.316.

- **Life expectancy of the technology:** The expected lifetime of the main components of the solar-powered domestic rice processing technologies is 5–10 years for the rice husker, the rice polisher, the control system and smaller components (cables, inverter). The PV modules and the frame holder have to be replaced after 20 years, batteries last 2–4 years.

- **Scale:** The system requires 25 Wh of electricity per kg of white rice and has a productivity of about 120 kg/day.

Costs

Capital costs: In recent years, the price of solar PV has dropped, making it more affordable and more competitive with diesel. The cost for a small 500 Wp solar mill to serve a village of about 40–80 households was taken to be US$3,000–5,000. The following tables summarizes size, costs and lifetime of the main components of a Agsol rice mill. Costs of a Agsol system are given (Table 4.41). Basic expertise is required for installation or maintenance.

TABLE 4.41. Typical costs for components of a small-scale solar-powered rice processing technology.

Equipment costs	Capacities	Costs (US$)	Life (years)
Rice husker	~45 kg/h	1,700	5–10
Rice polisher	~35 kg/h	1,500	5–10
PV modules and frame holder	500 W peak	720	20
Battery	40 Ah	300	3
Electrical cables, accessories, and inverter for small appliances	2.5 kW inverter (peak power)	240	5–10
Control system		390	5–10
TOTAL		**4,850**	**20**

Source: Authors.

Maintenance costs:

- cleaning sieve on polisher every two weeks; a simple operation for which Agsol supplies tools;
- replacement of carbon brushes on DC motor; Agsol uses brushed motors as they are robust and cost-effective, but brushes need changing every 500–2,000 hours. Agsol supplies spare brushes for about US$5/set. The frist two sets are provided by Agsol;
- replacement of rubber rollers on husker: every 500–1,000 hours for US$150/set from Agsol, or sourced locally as they are standard parts;
- new drive-belts are required every 250–500 hours and cost US$25 for the rice husker and US$15 for the polisher;
- batteries need replacement every 2–4 years at a cost of US$300; and
- about 1 hour of maintenance work per week for the mill.

Operating cost: The rice husker handles about 45 kg/h of raw rice and the rice polisher 35 kg/h. Therefore, processing 50 kg of rice requires about 2.5 h/day. To hull 26,000 kg of paddy rice, the mill requires about 550–600 h/year, and additional 600 h/year are required for polishing. These activities can be carried out in about 215 days/year, considering 6 hours of milling per day, one harvest per year. This operation time is higher than in the case of diesel mills, which can process 26,000 kg rice in about 260 h. Assuming a wage of US$1/hour and considering the time spent at the mill as opportunity costs, labour costs (excluding maintenance services) are US$13,000/year for the solar mill and US$260 for the diesel mill.[85]

85 Agsol provides a training session for local entrepreneurs showing them how to maintain the mill.

Benefits

Solar-powered rice processing avoids the costs of diesel, as well as the time and money spent to reach the nearest diesel mill. IRENA (2014) reported that decreased diesel fuel expenditure was seen as a major benefit by 27 percent of the beneficiaries, and a similar number noted that reduced travel time would be an advantage. On average, 2 h/day were spent on transport to the diesel mill, costing US$2/day. It is assumed that the farmers from the small villages will travel to the big diesel mill about 130 days/year to mill their rice.

One-third of stakeholders thought there would be less breakdown and maintenance with solar mills, but this perception is yet to be proven (IRENA, 2014). Women had a very strong interest in the "less complicated, less dirty" solar mills.

Agsol solar mills can improve the quality of the rice, since they use rubber rollers more typical of large-scale mills that are gentle on grains and reduce breakage and loss. Thus, it was assumed that a solar mill improves milling recovery (i.e. percent of head rice after milling) from 60 percent of the diesel mill to 65 percent, and reduces rice losses by 5 percent compared to a diesel mill. With the diesel mill, 10 percent of the paddy is wasted during processing, while the Agsol technology reduces this percentage to 5 percent. In PNG, the price of milled rice is variable but assumed to be US$1.5/kg. Therefore, the solar mill improves revenues from milled rice selling from US$28,080/year to US$29,640/year.

In some countries, the price of milled rice varies according to the percentage of broken rice.[86] Here it is assumed for simplicity that the price for white rice, of which 35–40 percent is broken, does not change. This assumption is quite appropriate for the PNG rice market. Moreover, many traditional diesel mills do not separate husk and bran, and rice bran is a highly valuable and nutritious co-product. It is further assumed that there are no market prices for rice husks and brains in PNG.

Financial profitability

The investment pays off after more than ten years, since the technology needs major replacement every five to ten years. Hence, the net benefits are fluctuating. The financial NPV is positive, as well as the IRR. Additional benefits of the technology, such as improved access to energy for the villagers, have yet not been included in the analysis.

86 See for instance: http://www.riceauthority.com/prices/.

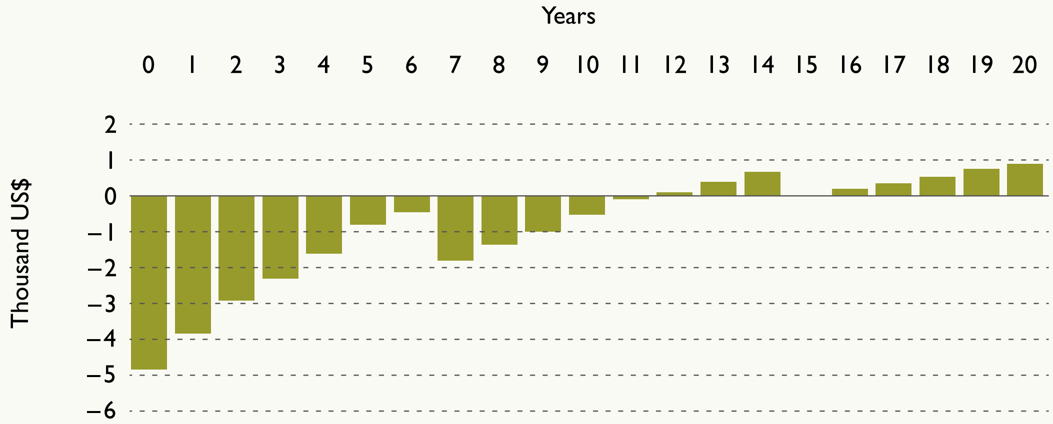
TABLE 4.42. Financial CBA of the Agsol solar-powered domestic rice processing technology.

	Unit	Agsol solar mill	Diesel mill	Notes
Life expectancy of the technology	year	20	5 years mill, 3 years generator	
		Financial costs		
Installation costs	US$	4,850	–	Pers. comm. Agsol, 2016
Replacement costs	US$	3,830 every 5–10 years (average 7.5)	–	Pers. comm. Agsol, 2016
Maintenance costs	US$/year	Approximately 400	–	Pers. comm. Agsol, 2016
Operating costs	US$/year	1,300	1,300	Assuming that farmers pay a service fee to use the diesel mill
Processing tariff (incl. diesel cost)	US$/year	0	780	Service fee: US$0.03/kg
Labour cost	US$/year	1,300	260	Wage: US$1/hour
Transport cost	US$/year	0	260	Assuming US$2/travel
		Financial benefits		
Revenues from selling rice	US$/year	29,640	28,080	Assumption: 5% reduction in broken rice
		Financial profitability indicators		
NPV	US$	932		
IRR	%	13		

Source: Authors and sources as indicated in Notes column.

FIGURE 4.49. Cumulative discounted net financial benefits over 20 years (solar-powered domestic rice processing).

Source: Authors.



Economic CBA

Value added along the value chain

Stakeholders in the PNG rice value chain include villagers, importers, wholesalers, retailers, agribusiness, commodity traders, investors, equipment suppliers and manufacturers, and others.[87]

PNG has a quite poorly developed domestic rice industry. Policies related to rice imports are relevant for the domestic value chain (ICCC, 2015). In this case study, the effect of rice imports is not considered. The final use of the domestic processed rice is typically local consumption in rural communities, since it is sold in local markets.

Wholesale and retail margins above factory gate price (FGP) were previously regulated at 10 percent and 11 percent respectively (ICCC, 2015), but this price control was removed in 2009. ICCC (2015) estimated that retail margins vary considerably across the regions (Table 4.43). Region average margins range from 9.5–21.2 percent. In the financial CBA, it is assumed that the solar rice mill reduces rice breakage and losses by about 5 percent compared to old diesel mills (i.e. 1,040 kg/year). Assuming a rice base price of US$1.5/kg and an average margin of 15 percent, the value added in the retail phase due to saving 1,000 kg/year of rice is about US$200–250/year/solar mill. Margins for the cost of delivering rice to the retailer were not considered as they can vary significantly.

Besides benefits in terms of food loss reduction (less rice is broken during milling) and the fact that more rice is made available in the value chain, no quality premium due to change in rice quality was assumed.

TABLE 4.43. Retail margin and cost component estimates by four different regions, 2014/15.

	Momase	%	Niugini Islands	%	Highlands	%	Southern	%
Imported raw material	PGK 2.20	57%	PGK 2.20	57%	PGK 2.20	58%	PGK 2.20	54%
Local processing	PGK 1.11	29%	PGK 1.11	29%	PGK 1.11	29%	PGK 1.11	27%
Local transport	PGK 0.05	1%	PGK 0.08	2%	PGK 0.05	1%	PGK 0.05	1%
Retail margin	PGK 0.52	14%	PGK 0.45	12%	PGK 0.42	11%	PGK 0.71	17%
Retail price	PGK 3.88		PGK 3.84		PGK 3.78		PGK 4.07	

Note: The estimated transport costs are only relevant to sampled outlets. Costs to outlets in areas farther from supplier distribution centres would be higher, leading to higher retail prices, lower margins, or a combination of both (ICCC, 2015).

Source: ICCC, 2015.

87 For example, out of the 30 people attending the VIA workshop in Lae, 70 percent were directly involved in agriculture, and 30 percent indirectly involved. Almost 80 percent of attendees sell small retail volumes of rice crops while 50 percent are involved at the wholesale scale. Fifty percent grow crops directly for themselves and one-third process crops themselves. All of them use diesel-powered mills to process crops, with 75 percent using non-electric diesel engines and 50 percent using electric motors on diesel generators. Grid electricity was used by 67 percent of respondents, only 8 percent process manually (women groups).

Subsidies and taxes

In the case of PNG, no diesel fuel subsidies exist. However, in other areas subsidies can offset the attractiveness of solar mills. No rice price subsidy or taxes have been considered in PNG.[88]

Assessment of environmental and socio-economic impacts

Soil quality

Impact	Relevance
No impact	–

Fertilizer use and efficiency

Impact	Relevance
No impact	–

Indoor air pollution

The introduction of a solar mill to replace a diesel system significantly reduces local air pollution in the community. This would benefit in particular women, since they are normally in change of agro-processing activities (IRENA, 2014). Common breakdowns and pollution related to the use of a diesel mill are reported as key drivers to invest in solar mills.

Impact	Relevance
No impact	–

Water use and efficiency

The technology has no direct impact on water use and efficiency. An indirect impact is avoided waste during processing due to the solar mill, which averts wastewater during rice production. According to Chapagain and Hoekstra (2010), in PNG the blue and green water footprint of rice is 0.0012 Mm^3/tonne of rice produced. Therefore, saving 1 tonne of rice per year can reduce wastewater of about 1,266,667 litres/year.

Impact	Relevance
Positive	Moderate

Water quality

The technology has no direct impact on water quality. However, the disposal of batteries at the end of their lifetime can become a major environmental issue if they are not disposed of correctly.

88 The PNG Government is developing a rice policy which has the objective of increasing domestic rice production. The ICCC (2015) estimated that the introduction of the tax incentives proposed under the rice policy will encourage domestic production. A subsidy or tax incentive on domestic production would not affect prices or the total quantity consumed by the market, but will increase domestic production and domestic producers' profits. However, this will be paid for by the taxpayer.

Impact	Relevance
Variable	High

Food loss

A Agsol solar mill uses rubber rollers, which reduce grain breakage and losses compared with conventional diesel mills. With diesel mills, the percentage of broken rice is around 10 percent of the paddy production, whereas with Agsol solar mill this is estimated to be about 5 percent. This change can lead to marginal increases in household consumption or rice sales in local markets. Assuming a production of 26,000 kg/year, about 1 tonne of rice per year can be saved by using the Agsol solar rice processing. The financial analysis incorporated benefits from food loos reduction of US$1,560/year (assuming a rice price of US$1.5/kg). Moreover, the avoided losses generate value added down the value chain.

Many traditional diesel mills do not separate rice husk and bran, a valuable co-product rich in various antioxidants that can be consumed by cattle or used for cooking oil production.

Impact	Relevance
Positive	High

Land requirement

The technology has no direct impact on land use change as the area occupied by the plant is negligible and similar to the benchmark.

Impact	Relevance
No impact	–

GHG emissions

In the financial analysis, the solar mill avoided the consumption of about 260 litres of diesel per year. Since combustion of a litre of diesel fuel emits approximately 3.16 kg of CO_2, the benefit of a solar mill amounts to about 822 kg CO_2/year.

The avoided GHG emissions can be monetized and included as benefits in the economic CBA. As for the other case studies, a SCC of US$36 US$/tonne was assumed. The monetized benefit due to GHG emission reductions is thus US$30/year.

Impact	Relevance
Positive	Moderate

Access to energy

PNG has a very low electrification rate. Only between 10–12.4 percent of PNG households have access to electricity (World Bank, 2013). Recently, mobile phone charging has been acting as a driver for increasing access to electricity for lighting, televisions and refrigerators. A PV system for rice mills can be designed to power small appliances, thus improving access to energy up to Tier 3. Larger PV systems can be a power platform for other energy services such as household energy or small business, distributed energy. The more machines added to the PV system, the greater the return on investment.

Agsol estimated that the solar mill can provide household energy for a value of US$2/day, in addition to the energy for the rice mills. The system can power other appliances such as phone batteries and small electric appliances. This could result in a benefit of US$600/year for the farmers in small villages if fully exploited. Improved access to modern energy has been proven to preferentially benefit women and children.

The extent to which improved access to a milling service at village level will promote gender equality and social inclusion depends on how the service is run and by whom. For example, the tariff to access the energy services would need to be set at a level to cover full costs while also ensuring that the service is accessible to all.

Impact	Relevance
Positive	High

Household income

By comparing solar with traditional diesel rice processing, the main impact on household income is through the off-set of typical household expenditures on diesel, transport, and milling services. Moreover, Agsol solar mills increase household income by reducing rice grain breakage and losses.

Without considering income generation from access to energy (e.g. mobile phone charging), the total net income benefits for small villages amount to an average of US$1,560/year. By assuming that about 50 households live in these small remote villages, the income benefits are on average about US$30/household/year.

Although the benchmark scenario for the analysis is a centralized diesel-powered mill, it should be considered that poor women who previously manually milled rice now have access to the Agsol solar rice mill. This can greatly increase the productivity of rice processing, from 1–10 kg/h (depending on how many household members participate) to 20 kg/h, which increases both household consumption of rice as well as income from more rice sold.

Agsol solar mills reportedly increase women's participation in this activity. It follows therefore that if a woman (or a group of women) is more involved in the management and operation of a village solar milling service, she has the potential to generate a higher income (providing that tariffs are collected and the whole service is financially viable). When women are able to contribute more to household income, they are economically empowered and better able to influence decision-making at home, in groups and in the community. There is a risk that men might take over the village-level solar rice processing service from women if it proves profitable.

Impact	Relevance
Positive	High

Time savings

Compared to large diesel mills, Agsol solar mills require more time to process the same quantity of rice. However, the possibility of installing solar mills in smaller villages can significantly reduce the time spent to transport to and from small villages, as accounted for in the financial CBA. In the absence of mechanized mills in small villages, women are more likely to resort to manually milling rice, which is both time-consuming and relatively unproductive. In this case, the Agsol solar rice mills have the potential to significantly save women's time and hence promote gender equality.

Overall, considering the benchmark scenario, the transport time avoided is partly offset by the additional time spent milling at the solar mill. Therefore, no relevant additional time saving is accounted for due to the energy intervention.

Impact	Relevance
Variable	Moderate

Employment

The introduction of the solar mills does not create direct employment since the system is typically owner-operated and does not require the presence of technical agents (Agsol trains the mill owners). So far, Agsol has trained several entrepreneurs in off-grid settlement, creating value added in the community.

Agsol currently employs four staff in PNG for wages between US$200–800/fortnight for unskilled labour. Agsol has already sold approximately 60 hullers and 55 polishers, and has purchase orders for another 50 hullers and 50 polishers (Pers. comm., Agsol, 2016). Considering that Agsol employees provide support services to each mill, the value of this service can be translated into around US$300/year of extra wages.

Impact	Relevance
Positive	Moderate

TABLE 4.44. Summary of environmental and socio-economic impacts (solar-powered domestic rice processing).

	Indicator	Impact
	Soil quality	No impact
	Fertilizer use and efficiency	No impact
	Indoor air pollution	No impact
	Water use and efficiency	About 1.27 million litres/year
	Water quality	Variable
	Food loss	US$1,560/day
	Land requirement	No impact
	GHG emissions	US$30/year
	Access to energy	US$600/year
	Household income	US$1,560/year (50 hh)
	Time saving	Variable
	Employment	US$300/year

Note: Food loss and household income benefits are already incorporated in the financial CBA.
Green = positive impact, yellow = variable impact, red = negative impact.

Source: Authors.

Economic profitability

The benefits from GHG emission reduction, household energy, and employment are monetized in the economic CBA. The economic NPV thus calculated is very positive (US$10,949) and the economic IRR is around 43 percent (Table 4.45). By including these monetized co-benefits, the pay-back time of the technology is reduced to less than 3 years (Figure 4.51).

TABLE 4.45. Economic CBA of the case study (solar-powered domestic rice processing).

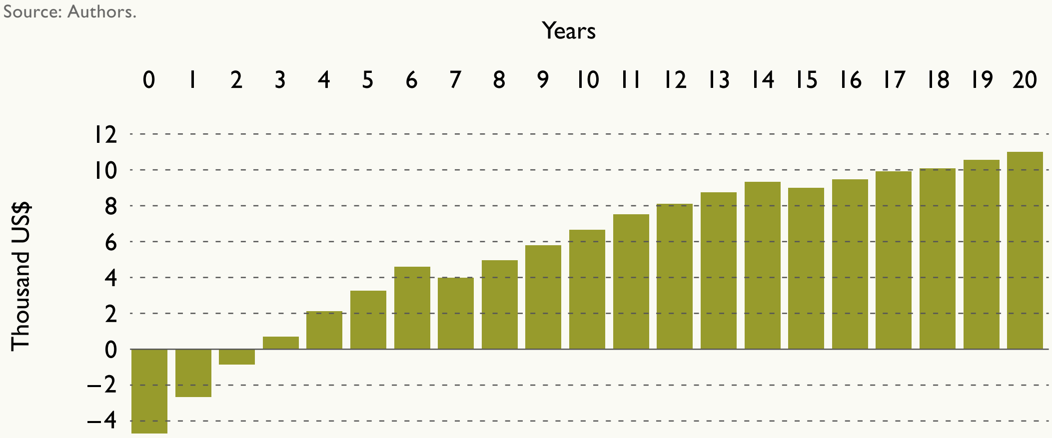
	Unit	Agsol solar mill	Diesel mill	Notes
Economic benefits				
Value added along the value chain	US$/year	200–250	0	Assuming rice price of US$1.5/kg and average margin of 15%
Environmental and socio-economic benefits				
GHG emission reduction	US$/year	30	0	Assuming 260 litres diesel are avoided
Access to energy	US$/year	600	0	Assuming US$2/day
Employment	US$/year	300	0	Pers. comm. Agsol, 2016
Economic profitability indicators				
NPV	US$	10,949		
IRR	%	43		

Note: An exchange rate of US$1 = PGK 3.165 and a discount rate of 11 percent were assumed for the analysis.

Source: Authors and sources as indicated in Notes column.

FIGURE 4.50. Cumulative discounted net economic benefits over 20 years (solar-powered domestic rice processing).

Source: Authors.



Results

The cumulative discounted net financial and economic benefits of the solar-powered domestic rice processing are compared (Figure 4.52) assuming the benchmark was a distant traditional diesel mill. If assuming a rice production of 26,000 kg/year, the financial investment pays back in about 5 years. An increase in key parameters such as the price of rice, quantity of rice processed, price of diesel or interest rate, could further increase the financial benefits of the technology.

The economic analysis highlights the benefits of this technology in terms of value added at the retail stage (due to avoided food losses during the processing stage), improved access to electricity, GHG emission reductions, and employment creation. Taking into consideration these co-benefits, the NPV of the investment becomes more positive and it pays back in less than 3 years.

In addition to the economic benefits internalized in the analysis, the technology would bring additional (non-monetized) benefits in terms of water efficiency at the production stage since there is less rice grain damage and fewer losses at the mill. Since the disposal of solar energy batteries can become a major environmental issue if not correctly done, the impact on water quality needs to be particularly monitored. Similarly, even if the additional time spent milling is likely to offset the transport time to bigger diesel mill, the impact on time saving is not straightforward.

FIGURE 4.51. Cumulative discounted net financial and economic benefits over 20 years (solar-powered domestic rice processing).

Source: Authors.

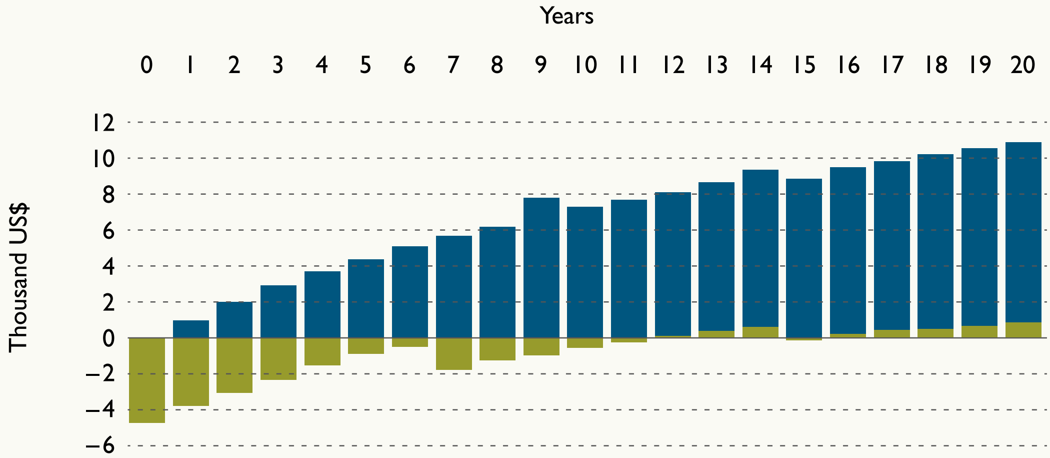
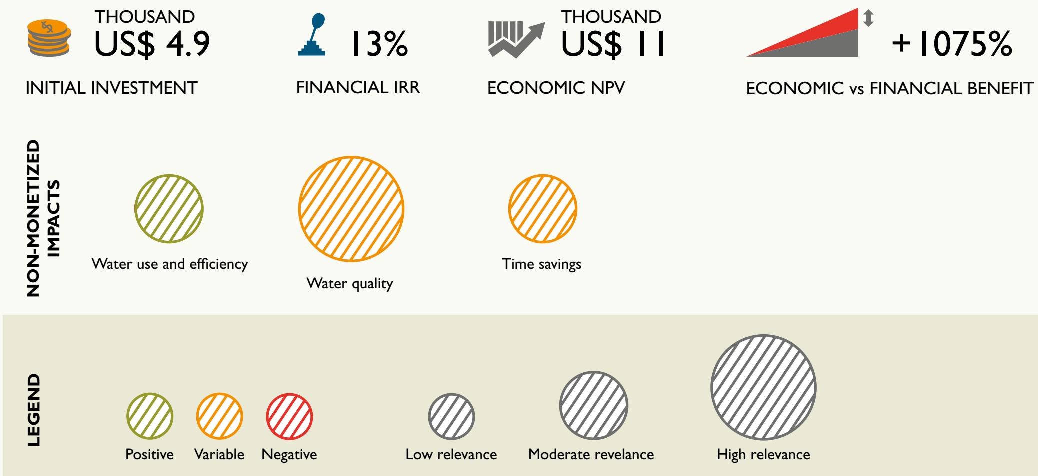
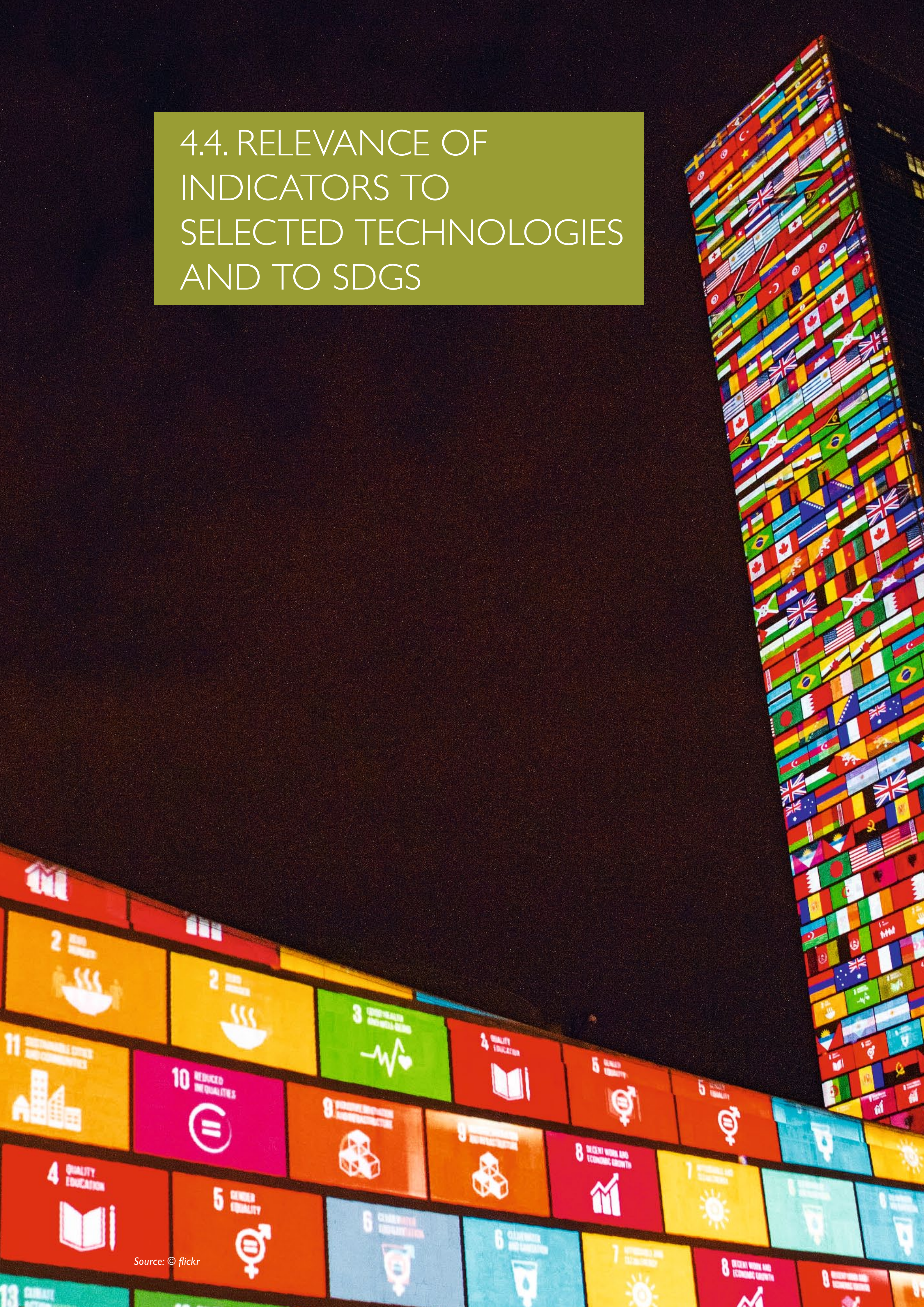


FIGURE 4.52. Key figures of the case study (solar-powered domestic rice processing).

Source: Authors.



4.4. RELEVANCE OF INDICATORS TO SELECTED TECHNOLOGIES AND TO SDGS



Source: © flickr

Not all sustainability indicators outlined in the methodology (Section 3) are relevant for all technologies. For example, only a few technologies may need a large land area or lead to a shift in land use to make the "land requirement" indicator worth mentioning. Also, solar technologies usually have no direct impact on water quality, but can have an indirect impact on the amount and efficiency of water used.

The relevant impact indicators chiefly depend on the specific case study but also on the specific energy intervention. Table 4.46 provides guidance on the relevant impact indicators for selected technologies, based on the advantages and disadvantages of each technology illustrated in the descriptions of this section. The impact can be positive or negative.

The impacts of the selected case studies are not necessarily the same ones that can be found during the implementation of an intervention on the ground. Certain expected impacts may not be relevant for the specific case or, on the contrary, an impact that is typically not relevant for the technology may become relevant when assessed in a specific context.

TABLE 4.46. Relevance of impact indicators to selected technologies.

INDICATOR	Biogas for power generation	Biogas-powered domestic milk chiller	Solar milk cooler	Solar cold storage for vegetables	Solar-powered water pumping	Rice husk gasifi-cation	Solar-powered rice pro-cessing
ENVIRONMENTAL							
Soil quality	X	X				X	
Fertilizer use & efficiency	X	X					
Indoor air pollution	X	X					X
Water use & efficiency	X	X	X	X	X		X
Water quality	X	X	X			X	
Food loss	X	X	X	X			X
Land requirement	X					X	
GHG emissions	X	X	X	X	X	X	X
SOCIO-ECONOMIC							
Access to energy	X	X	X	X	X	X	X
Household income	X	X	X	X	X	X	X
Time savings	X	X			X		X
Employment	X	X	X	X	X	X	X

Source: Authors.

The introduction of selected clean energy technologies and the associated environmental and socio-economic impacts highlight synergies towards the achievement of the SDGs. Adopted at the United Nations General Assembly in September 2015, several of the 17 goals relate directly to agrifood production and processing and clean energy, such as SDGs 2, 3, 5, 6, 7, 8, 12, 13 and 15 (Table 4.47).

The measurement of the non-monetized co-benefits of clean energy interventions in the agrifood chain provide useful information that can be used for the measurement of relevant SDG targets. There are strong links between the SDG targets, the selected clean energy technologies, and the indicators used in the CBA in this study (Table 4.47). The relevant SDG targets are reported in Table 4.48. The impacts associated with the introduction of an agrifood energy technology can be positive or negative, and they are consistent with the CBA indicator set proposed to measure non-monetized impacts (Section 3.3).

TABLE 4.47. **Relevance of selected agrifood energy technologies to the SDGs and respective targets.**

SDGs / Technology	2 ZERO HUNGER	3 GOOD HEALTH AND WELL-BEING	5 GENDER EQUALITY	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	15 LIFE ON LAND
Biogas for power generation	Targets 2.1, 2.2, 2.3 and 2.4	Target 3.9	Target 5.8	Targets 6.3 and 6.4	Target 7.1	Targets 8.2 and 8.5	Targets 12.2, 12.3 and 12.4	Target 13.2	Targets 15.3 and 15.5
Biogas-powered domestic milk chiller	Targets 2.1, 2.2, 2.3 and 2.4	Target 3.9	Target 5.8	Targets 6.3 and 6.4	Target 7.1	Targets 8.2 and 8.5	Targets 12.2, 12.3 and 12.4	Target 13.2	Target 15.3
Solar milk cooler	Targets 2.1, 2.2 and 2.3	–	Target 5.8	Targets 6.3 and 6.4	Target 7.1	Targets 8.2 and 8.5	Target 12.3	Target 13.2	–
Solar cold storage for vegetables	Targets 2.1, 2.2 and 2.3	–	Target 5.8	Target 6.4	Target 7.1	Targets 8.2 and 8.5	Targets 12.2 and 12.3	Target 13.2	–
Solar water pumping	Target 2.3	–	Target 5.8	Target 6.4	Target 7.1	Targets 8.2 and 8.5	Target 12.2	Target 13.2	–
Rice husk gasification	Targets 2.3 and 2.4	–	Target 5.8	Target 6.3	Target 7.1	Targets 8.2 and 8.5	Target 12.4	Target 13.2	Targets 15.3 and 15.5
Solar-powered rice processing	Targets 2.1, 2.2 and 2.3	Target 3.9	Target 5.8	Target 6.4	Target 7.1	Targets 8.2 and 8.5	Targets 12.2 and 12.3	Target 13.2	–

Surce: Authors.

TABLE 4.48. Definitions of the SDGs targets included in Table 4.47.

Target 2.1	By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round.
Target 2.2	By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons.
Target 2.3	By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets, and opportunities for value addition and non-farm employment.
Target 2.4	By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding, and other disasters and that progressively improve land and soil quality.
Target 3.9	By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination.
Target 5.8	Enhance the use of enabling technology, in particular information and communications technology, to promote the empowerment of women.
Target 6.3	By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.
Target 6.4	By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.
Target 7.1	By 2030, ensure universal access to affordable, reliable, and modern energy services.
Target 8.2	Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors.
Target 8.5	By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value.
Target 12.2	By 2030, achieve the sustainable management and efficient use of natural resources.
Target 12.3	By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses.
Target 12.4	By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment.
Target 13.2	Integrate climate change measures into national policies, strategies and planning.

Target 15.3	By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world.
Target 15.5	Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species.

Source: UN Sustainable Development Knowledge Platform (https://sustainabledevelopment.un.org/).

5. DISCUSSION AND RECOMMENDATIONS

5.1. KEY FINDINGS

This study identified multiple benefits from investing in clean energy interventions in milk, vegetable and rice agrifood value chains. **The total benefits achieved from an investment are usually greater than the simple gains as measured by the financial IRR or NPV.** When measured in economic terms (including externalities, which in some cases can be monetized),[89] the **co-benefits can significantly affect an investment decision based only on financial returns.**

The change in the economic performance of a clean-energy technology intervention also contributes to the environmental and social performance of the value chain. The methodology described in Section 3 enables the sustainability performance to be measured and then used in the subsequent steps of the value chain (Section 2.4 Sustainability of value chains).

An economic CBA does not provide information on the economic efficiency, political feasibility, legality, or social and cultural acceptability of a project. Nevertheless, it can be **used to identify good practices for the distribution of costs and benefits across stakeholders to inform decision-makers** about the distribution of impacts of an investment.

Such analysis cannot provide accurate quantitative estimates of hypothetical costs and benefit flows but it can only provide, with a reasonable degree of confidence, an indication of a range of NPVs within which the true NPV may fall.

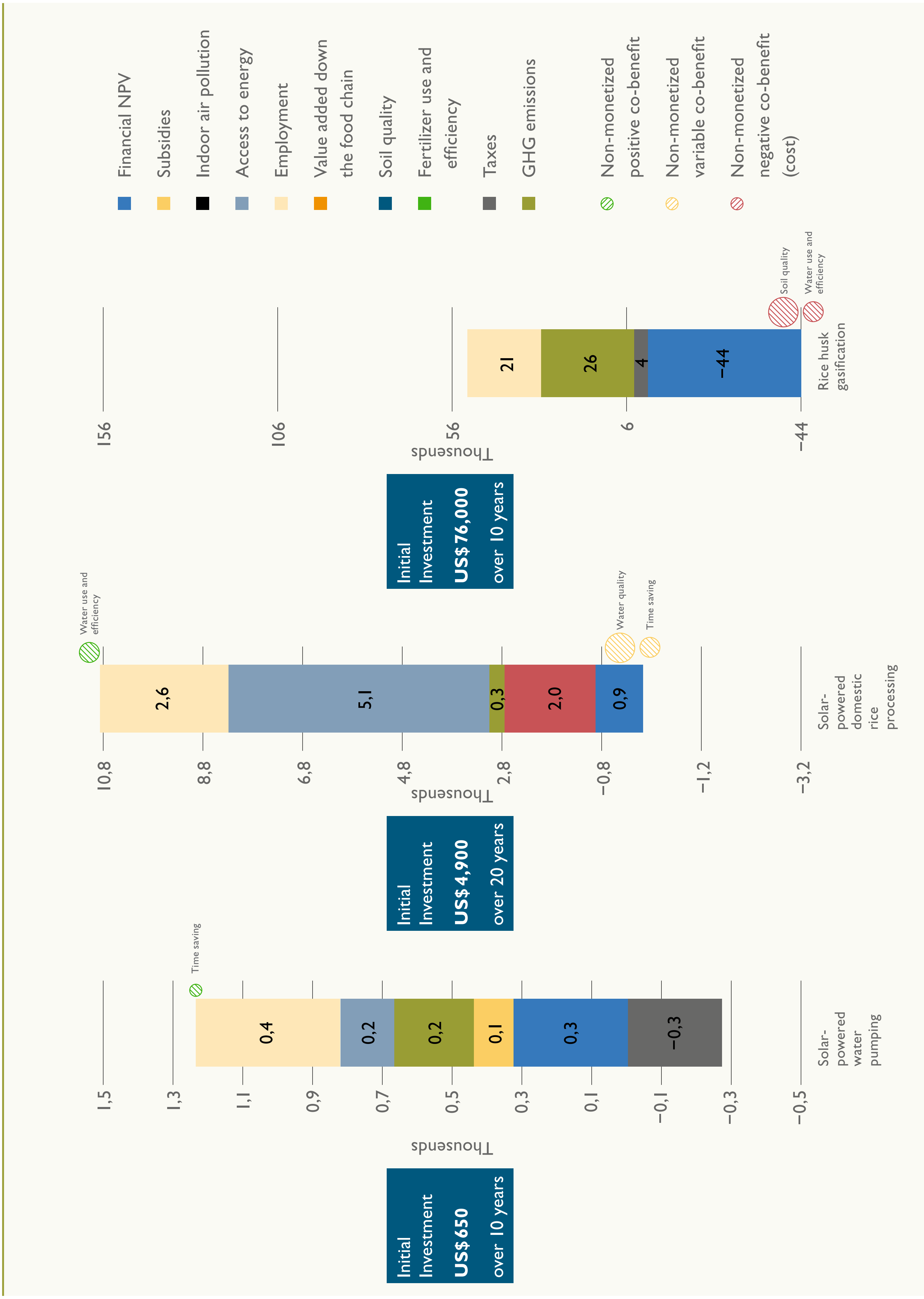
Clean energy, pro-poor interventions can potentially affect gender issues where specific activities are typically carried out either by men (such as running a diesel engine) or by women (such as tending a domestic biogas plant, or taking milk for sale to the local market). Gender analysis in the case studies was limited owing to a lack of gender-sensitive information available, including sex-disaggregated data. Benefits specific to each case study rather than general trends (by energy intervention or value chain) were evident. **There were no broad trends from the case studies as to how gender issues would benefit from clean-energy interventions in general.** Each one has specific benefits.

89 A *financial analysis* examines the returns to project stakeholders and provides the foundation for an *economic analysis*, which is carried out to ascertain the *desirability* of a project in terms of its net contribution to the economic and social welfare of the state or nation as a whole.

Results of more disaggregated analyses than those visualized at the end of each case study (Section 4) can lead to more general conclusions discussed below (Figure 5.1). These conclusions highlight that the success of the initial financial investment needed to introduce the clean energy intervention can be assessed by the financial returns to the investor and/or operator. However, co-benefits or costs that do not contribute to financial returns can have an important impact on society. These are highlighted in Figure 5.1 along with non-monetized and/or non-quantified impacts.

FIGURE 5.1. Summary of initial investments, financial and economic returns, including co-benefits for each of the six case studies.

Source: Authors.



Initial Investment
US$650
over 10 years
Thousands
1,5
1,3
1,1
0,9
0,7
0,5
0,3
0,1
–0,1
–0,3
–0,5
Time saving
0,4
0,2
0,2
0,1
0,3
–0,3
Solar-powered water pumping
Initial Investment
US$4,900
over 20 years
Thousands
10,8
8,8
6,8
4,8
2,8
–0,8
–1,2
–3,2
Water use and efficiency
2,6
5,1
0,3
2,0
0,9
Water quality
Time saving
Solar-powered domestic rice processing
Initial Investment
US$76,000
over 10 years
Thousands
156
106
56
6
–44
21
26
4
–44
Soil quality
Water use and efficiency
Rice husk gasification
Financial NPV
Subsidies
Indoor air pollution
Access to energy
Employment
Value added down the food chain
Soil quality
Fertilizer use and efficiency
Taxes
GHG emissions
Non-monetized positive co-benefit
Non-monetized variable co-benefit
Non-monetized negative co-benefit (cost)

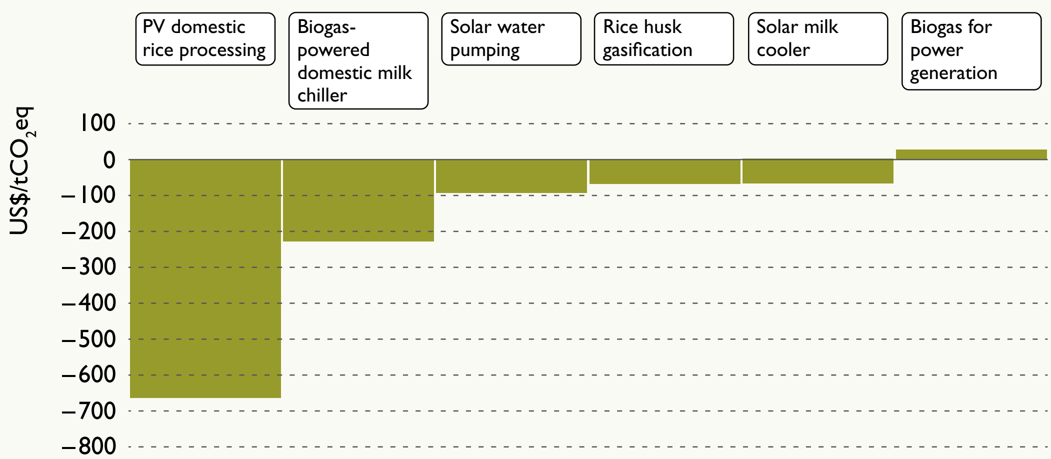
Even in a case where an investment is financially unattractive, such as the rice husk gasification case study in Cambodia or the biogas for power generation case study in Kenya, the overall economic investment can become positive when net co-benefits are included. In such cases, from the societal perspective, it could make sense to support or subsidize the investment to make it financially attractive.

One important effect from clean-energy interventions is the reduction of fossil fuel consumed, and hence the amount of GHGs emitted. The co-benefit of the avoided social cost can be significant but is heavily dependent on the monetary value given to it. In this report, a conservative social cost of US$36/t$CO_2$ was assumed (see Section 4).[90] However, it is appreciated that social cost estimates vary widely in the literature with a range between US$43–US$220/tCO_2 (US IAWG, 2013; Moore and Diaz, 2015). A study in Kenya (True Price and IDH, 2016) used a social cost of US$110/t$CO_2$. By replacing the assumed social cost with the Kenyan study figure, the co-benefit share due to GHG emission reduction for the case studies would be around three times larger.

When undertaking a CBA, it could be useful to assess the performance of energy interventions to mitigate GHG emissions in the case studies as additional information when making investment choices. The GHG mitigation cost of selected interventions assessed in this report can be expressed as economic NPV (including monetized co-benefits and costs) divided by the total amount of CO_2eq reduced by the intervention during its lifetime (Figure 5.2). Since all the case studies showed a positive economic NPV, the associated mitigation cost is always negative. In other words, there is always an overall economic benefit associated with GHG mitigation over the timeframe of the investment analysed. The initial investment needed to avoid emitting 1 tonne of CO_2eq varies (Figure 5.3), suggesting that interventions with relatively low mitigation costs are not necessarily those with the lowest initial capital investment per tonne CO_2eq.

FIGURE 5.2. Mitigation costs (economic NPV/CO_2eq avoided) for the six case studies.

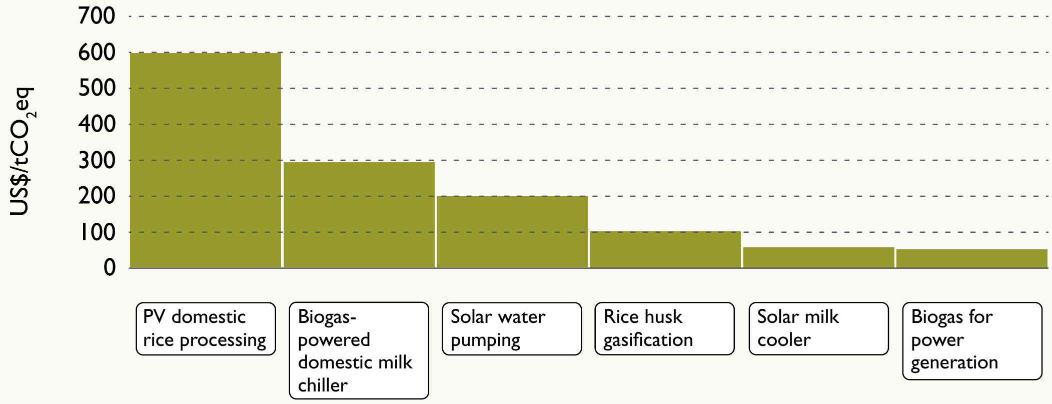
Source: Authors.



90 Based on Yohe et al., 2007 and EPA, 2016.

FIGURE 5.3. Initial investment per tonne of GHG avoided for the six case studies.

Source: Authors.



The co-benefits of an investment in a clean-energy intervention are usually distributed across a range of stakeholders. An analysis of this distribution can provide important information from a development perspective (Figure 5.4). For each dollar invested in a specific intervention, a share of the total benefit translates into a financial return for the operator and/or the investor, with other benefits distributed to society. **The interventions which maximize the non-financial returns are expected to spread the benefits amongst society.**

A deeper analysis could also consider the benefits which would possibly remain within the country (such as the financial benefits where the investor is a national citizen). However, such analysis is highly investment-specific.

On the basis of the six clean-energy intervention case studies analysed (a very limited sample) the **smaller-scale applications appear to achieve more diversified co-benefits, especially socio-economic benefits** (Figure 5.4). These are **relevant in economic terms** and can significantly exceed the financial benefits. Examples include small-scale milk chillers, small-scale solar water pumps and solar-powered rice processing systems. These energy interventions typically target farmers and their families as well as local food processors. On the opposite end, the co-benefits of larger-scale energy mainly go to employment and GHG emissions.

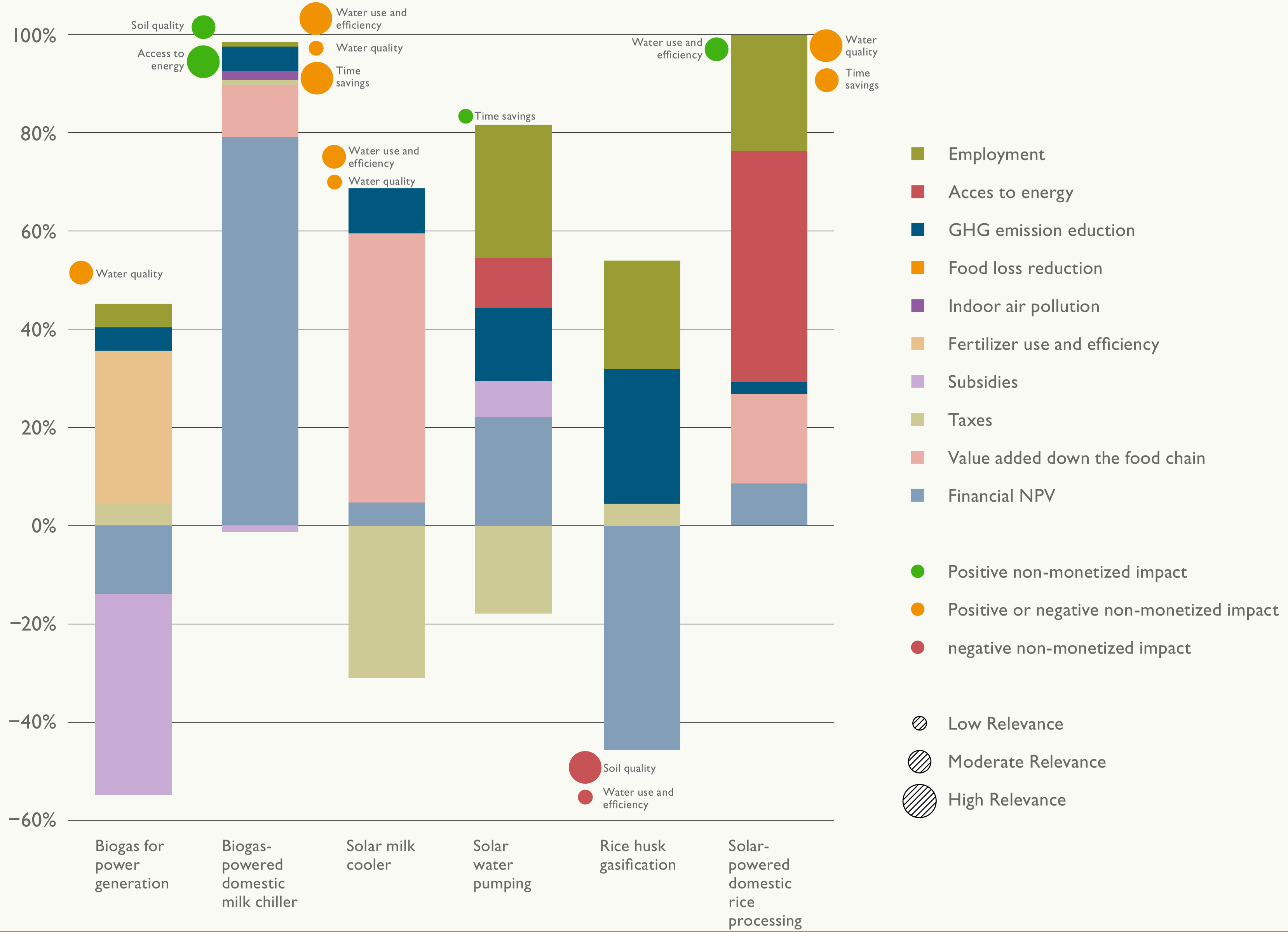
The economic performance obviously depends on the specific context under which an energy intervention is introduced, since **local taxes, markets, energy prices, and subsidies can significantly change the results.** For example, where deployment of renewable energy-driven technologies is subsidized (such as by governments providing an FiT for biogas-for-electricity generation plants), the investment can be uneconomic since the subsidies are a cost on society.[91] The actual cost of energy from a conventional source in an intervention (such as grid electricity tariffs or diesel fuel price), and the

91 This is particularly true for fossil fuel subsidies, since the cost of the subsidy adds to the societal cost in terms of environmental pollution.

FIGURE 5.4. Shares of financial and non-financial co-benefits and costs for the six case studies.

Note: Taxes and subsidies can be positive or negative benefits. For example, (i) if the intervention is subsidized, that subsidy is a cost for society; (ii) if the intervention reduces the amount of taxes paid to society, this is a negative benefit (= a cost) for society.

Source: Authors.



extent of any government subsidy, are key variables to determine the economic attractiveness of a competing clean-energy option. **In remote rural areas where access to modern energy services is currently constrained, a clean-energy intervention can have the added benefit of reducing drudgery, particularly for women, and improving lifestyles.**

The **co-benefit of reducing food losses or improving food quality due to the introduction of a clean-energy** technology (as is the case for milk cooling centres and solar-powered cold storage systems) can be very relevant. It can increase the amount, hence total value, of food products that enter into the market. This can have an impact on subsequent steps along the value chain after the point where the intervention takes place. For example, introducing a milk chiller at small-farm level will reduce milk spoilage and can have positive impacts in the context where local milk supply is limited and the local market is not well developed or functioning efficiently (as is typical in rural and remote areas of developing countries). The adopter of the clean-energy technology will directly benefit from increased revenue, but additional value may also occur along the supply chain such as for milk processors, transport businesses and retailers. **Food loss reduction thus has a multiplier effect, which tend to be more significant in longer value chains** (such as the milk chain, compared to rice or vegetables).

Positive and negative impacts of the seven energy interventions analysed in this report have also a direct link with achieving several of the 17 Sustainable Development Goals, in particular:

- Zero hunger (SDG 2)
- Good health and well-being (SDG 3)
- Gender equality (SDG 5)
- Clean water and sanitation (SDG 6)
- Affordable and clean energy (SDG 7)
- Decent work and economic growth (SDG 8)
- Responsible consumption and production (SDG 12)
- Climate action (SDG 13)
- Life on land (SDG 15)

Investment in energy interventions in agrifood chains is more closely linked with the achievement of SDGs 2, 6, 7, 8, 12, 13 and 5 (see Table 4.47). The interventions involving biogas (and digestate) production have crosscutting impacts (positives and negatives) on all nine of the above-mentioned SDGs, while the solar-based interventions impact on a smaller number. However, further analysis of more case studies is required to confirm these linkages.

5.2. KNOWLEDGE GAPS

Whilst informative, **the key findings from the six case studies analysed cannot be generalized** with a high degree of confidence since the sample is too limited and more cases are needed for validation. Organizations such as PAEGC Partners, REEEP, and other contributors to this study that are able to access data and information on the impacts of energy interventions in food chains from their project portfolios, could help fill this knowledge gap.

Knowledge gaps are also associated with the methodology applied. The study of government policies is often through the lens of economic efficiency, equity, public economics, and the ability to quantify and monetize project impacts. **However, no unique method exists to monetize positive and negative environmental and social impacts.** For this reason, the methodology used is non-prescriptive of how impacts should be monetized but rather provides guidance to measure non-monetized environmental and socio-economic impacts in a quantitative manner. This is achieved introducing a set of 12 indicators which can be used to measure impacts of energy interventions in food chains.

This set of indicators is specifically designed to be applied to any energy intervention (typically an energy efficiency or renewable energy intervention) in the food chain in a consistent manner. However, the indicators selected and the associated methodology may prove to be irrelevant or unsuitable to cover the broad range of possible energy interventions. **A systematic pilot testing of the indicators set, encompassing a diversified number of energy interventions, would inform the revision and adjustment of the indicators.**

Countries where the indicators and the economic CBA are tested will obtain valuable information regarding the performance of energy interventions. **Testing the indicators can provide an understanding of how to establish a systematic monitoring of energy investments in the food chain on the basis of a consistent methodology.** This would clarify how contributions of food and energy investments to national sustainable development are evaluated. It is also appreciated that, given the data requirements, a broad range of scientific expertise as well as technical and financial assistance may be required to undertake and use a CBA to inform policymaking.

5.3. RECOMMENDATIONS

The following is a set of general recommendations on how best to support rural economic development by promoting clean energy solutions:

(i) From a sustainable development perspective, investment choices should always consider non-financial costs and benefits. For the energy interventions analysed, net economic benefits largely exceed net financial benefits. In some cases, the net economic benefits are positive even if the investment is financially unattractive.

(ii) Since the monetization of all co-benefits can be complex, it is recommended to adopt a consistent set of indicators to measure non-monetized impacts of energy interventions in agrifood chains. The set of indicators used here serves this purpose but could be further piloted and revised.

(iii) The interventions that maximize non-financial returns should be prioritized from the perspective of sustainable development – since they are expected to spread the benefits amongst society.

(iv) Smaller-scale technologies should be prioritized to maximize the diversification of co-benefits. Such systems typically target farmers and their families as well as local food processors. In this context, a clean-energy intervention can have the added benefit of reducing drudgery and improving lifestyles (for example, access to electricity can be used to start new businesses).

(v) Energy interventions that reduce food losses or increase food quality should be prioritized since the co-benefits down the food chain can be major – especially in food insecure regions. Energy interventions that reduce food wastage near the beginning of a long value chain have important multiplier effects, since more food is available. Longer food value chains (i.e. with a wider range of actors such as the milk chain compared to the rice chain) can potentially benefit the most from interventions reducing food losses. For example, the local production of better quality milk to meet the growing demand for milk products in poor isolated regions has strong economic development potential, especially when local demand of good quality milk exceeds the availability (such as in the case of biogas milk cooling in rural Tanzania).

(vi) Access to inputs, services and decision-making between men and women – at home, on the farm, in cooperatives and throughout the value chain – mean that energy interventions have an impact, positive and/or negative, on gender equality. However, no general trend by energy intervention or value chain could be drawn from the analysis and it is recommended to assess impacts on gender issues on a case-by-case basis. The systematic promotion of gender equality in energy interventions should be improved, from design and problem identification to complementary services, monitoring and evaluation and the recruitment of staff.

(vii) An economic CBA should be undertaken as a guide to choose between investments, assuming that data and information exist that provide an accurate estimate of net benefits. In addition, economic efficiency, political feasibility, legality, social, and cultural acceptability of a project are likewise important aspects to be considered as they can determine the success of an energy intervention.

(viii) In an economic CBA, it is important to carefully consider taxes, subsidies, and added value along the agrifood chain since they can significantly modify the results.

(ix) Since the assumed social cost of GHG emissions can be a major variable to determine economic co-benefits, it is important to use consistent assumptions when assessing and comparing different energy interventions.

(x) In off-grid areas or regions with an unreliable energy grid, it is important to prioritize energy interventions that contribute to energy access as a co-benefit (e.g. those that make surplus modern energy available for use by families and communities, including to those outside the specific food value chain). Access to clean, reliable and affordable energy, especially in rural areas of developing countries, will help reduce poverty, enable new businesses and can significantly decrease energy supply costs – including for simple energy services such as lighting or mobile phone charging. Synergies between energy needs for food and other village-level necessities should be considered when designing solutions that can meet diverse energy needs and maximize sustainable development impacts (e.g. a micro-grid with irrigation pumps and agro-processing equipment as anchor loads).

(xi) Investments in energy interventions in the agrifood chain have a direct impact on achieving the SDG targets since they can affect positively or negatively at least 9 of the 17 total SDGs. Synergies and trade-offs among SDGs and targets need to be carefully considered in a truly crosscutting and interdisciplinary perspective by giving special attention to the water-energy-food nexus.

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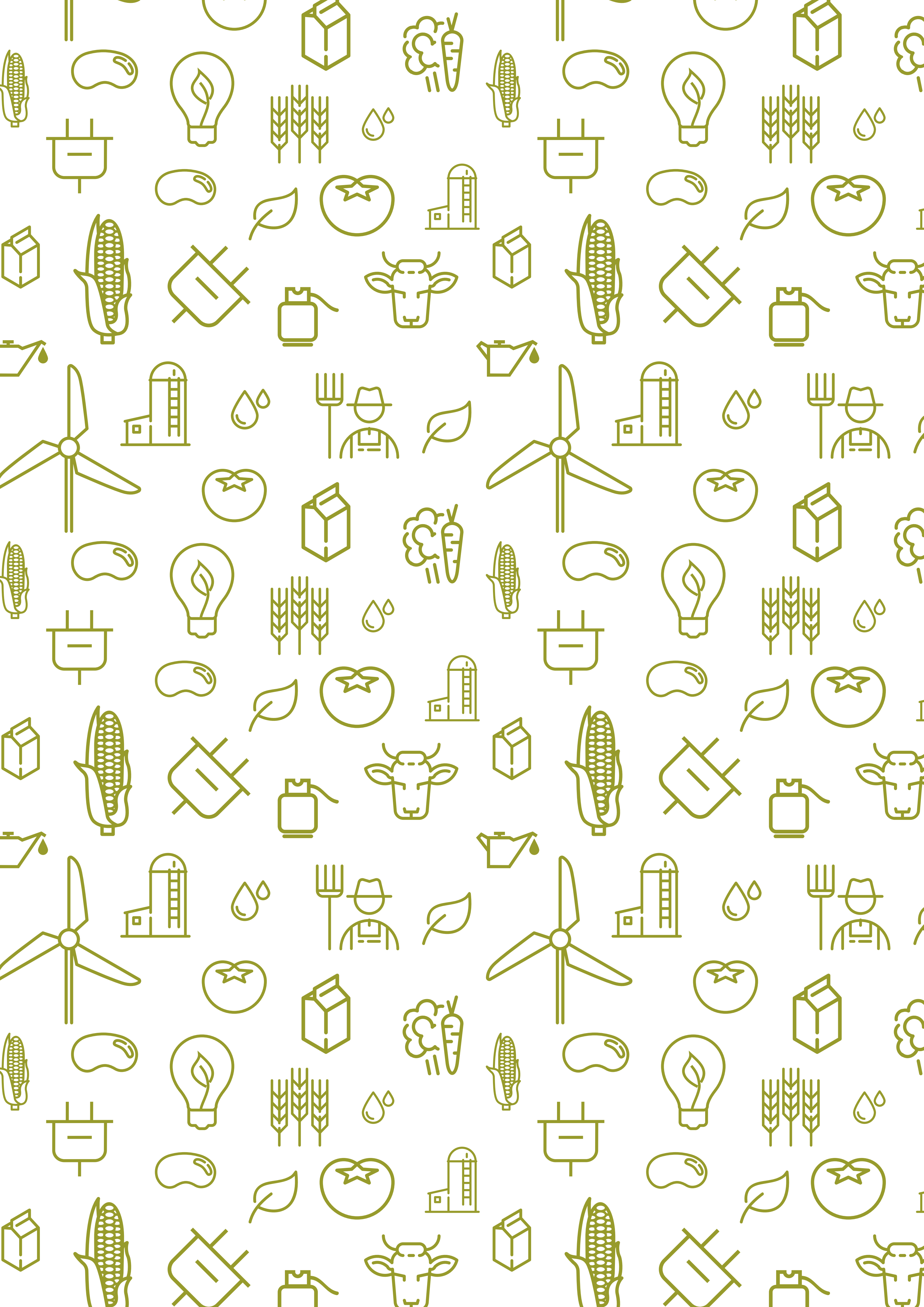

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