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Presented by:

Djibril BALLO

Water-Energy-Food integrated business models for decentralized renewable energy solutions: the case of agrophotovoltaics in Koutiala-Mali, SSA region

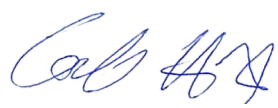
Defended on November 25, 2021 Before the Following Committee

Chair:	Lotfi Baghli	Pr.	University of Lorraine
Supervisor	Carlo Tacconelli	Dr.	Sapienza University of Rome
External Examiner	Daniel Yamegueu Nguewo	Dr.	2IE, Burkina Faso
Internal Examiner	Mohamed Choukri Benhabib	Dr.	Tlemcen University, Algeria

Declaration

I, Djibril BALLO, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Student name	Signature	Date
Djibril BALLO		16/01/2022

Supervisor Name	Signature	Date
Dr. Carlo Tacconelli		21/01/2022

CERTIFICATION

As candidate's supervisors, we approved this dissertation for submission and examination

Dr. Carlo Tacconelli

Signed:

Supervisor

Dr. Paolo Cherubini

Signed:

Co-Supervisor

ABSTRACT

In Africa, access to clean energy, water, and food security is a major problem, particularly in sub-Saharan Africa and even lower or inexistent in remote regions not connected to the electricity grid. The problem of water resources is essential and even vital for the populations in the Sahel zone particularly in Mali. In some regions of the country, conflicts between various uses of water, appear because of the fall of water tables, the early drying up of water bodies and the shrinking of productive spaces. Water supply and sanitation in Mali faces significant challenges. Poor water quality leads to potentially lethal diseases. In 2018, the Ministry of Energy and Water reported access rates to drinking water of 65.3% in rural areas, 74.7% in urban areas, and 68% at national widely. The low share and the underdevelopment of Water-Energy-Food for renewable mini-grids to ensure electricity and water accessibility for economic development in Africa especially in Mali are in-existent. Water-Energy-Food nexus can be employing at high level of efficiency in the development in Mali. In Koutiala, Water-Energy-Food integrated in business models is inexistent yet or the agrivoltaics systems are the best solutions for decentralized energy for water demand, provide the agricultural activities for food security and economic development without polluting the environment. Agriculture has become one of the reasonable economic sector in Mali, being the source of income through cash-crops and food-crops cultivation and Koutiala region is the big producer of cotton and other food crops. The sector is facing a number of difficulties due to lack of electricity, water mostly and it rains seasonally, in rural areas as well as lack of environmental and economical friendly technologies for electricity production, water pumping from the surface or underground water source to the farms for irrigation, in some cases small farmers are most vulnerable due to the rise of diesel prices to run the generator for irrigation. The system composed of 92.7 kW of solar PV array, 75kW of inverter is designed with PVsyst software to provide electricity, water in Koutiala region. The economic analysis of the two types of business models allowed us to identify the most profitable business model to adopt in the region. The different analyzes gave us the following results: the same LCOE equal €0.09/kWh, Present net Value (NPV business model 2) €131,073 is higher than the net present value (NPV business 1) €74,732, Internal Return Rate (IRR business model 2) 14% is higher than (IRR business model 1) 10%, the Payback Period (business model 1) 18 years is higher than the Payback Period (business model 2) 14 years. Since the NPV are positives and the IRR are higher than the real discount rate ($i_,$) so both of our business models are attractive and profitable but the business model 2 is economically more profitable.

Keywords: Agrivoltaic, Agriculture, Irrigation, energy, water pumping, food security

Résumé

En Afrique, l'accès à l'énergie propre, à l'eau et la sécurité alimentaire est un problème majeur, notamment en Afrique subsaharienne et encore plus faible ou inexistant dans les régions reculées non connectées au réseau électrique. Le problème des ressources en eau est essentiel et même vital pour les populations de la zone sahélienne notamment au Mali. Dans certaines régions du pays, des conflits entre les différents usagers de l'eau, apparaissent en raison de la baisse des nappes phréatiques, de l'assèchement précoce des plans d'eau et de la diminution des espaces productifs. L'approvisionnement en eau et l'assainissement au Mali sont confrontés à des défis importants. La mauvaise qualité de l'eau entraîne des maladies potentiellement mortelles. En 2018, le ministère de l'Énergie et de l'Eau a fait état de taux d'accès à l'eau potable de 65,3% en milieu rural, 74,7% en milieu urbain, et 68% à l'échelle nationale. La faible part et le sous-développement des mini-réseaux renouvelables Eau-Énergie-Alimentation pour assurer l'accessibilité à l'électricité et à l'eau pour le développement économique en Afrique notamment au Mali sont inexistant. Le lien eau-énergie-alimentation peut être utilisé à un haut niveau d'efficacité dans le développement du Mali. A Koutiala, l'intégration Eau-Energie-Alimentation dans les modèles d'affaires est encore inexistante or les systèmes agro-photovoltaïques sont les meilleures solutions pour l'énergie décentralisée pour la demande en eau, pour les activités agricoles, pour la sécurité alimentaire et le développement économique sans polluer l'environnement. L'agriculture est devenue l'un des secteurs économiques les plus importants au Mali, étant la source de revenus grâce aux cultures de rente et aux cultures vivrières. La région de Koutiala est le grand producteur de coton et d'autres cultures vivrières. Le secteur est confronté à un certain nombre de difficultés dues au manque de l'électricité, d'eau dans les zones rurales et l'absence de technologies respectueuses de l'environnement et de l'économie pour produire l'électricité, pomper des eaux de surface ou souterraines vers les fermes pour l'irrigation. Un système composé de 92,7 kW de panneaux solaires photovoltaïques et de 75 kW d'onduleur, est conçu avec le logiciel PVsyst pour fournir l'électricité et l'eau dans la région de Koutiala. L'analyse économique des deux types de modèles économiques nous a permis d'identifier le modèle économique le plus rentable à adopter dans la région. Les différentes analyses nous ont donné les résultats suivants : le même LCOE est égal à 0,09 €, la valeur nette actuelle (NPV business model 2) de 131 073 € est supérieure à la valeur nette actuelle (NPV business model 1) de 74 732 €, le taux de rendement interne (IRR business model 2) de 14 % est supérieur au (IRR business model 1) de 10 %, le délai de récupération (business model 1) de 18 ans est supérieur au délai de récupération (business model 2) de 14 ans. Comme les NPV sont positifs et les IRR sont supérieurs au taux d'intérêts alors on peut conclure que les deux business modèles sont profitables mais le business model 2 est économiquement plus rentable.

Mots-clés : Agrivoltaïque, Agriculture, Irrigation, énergie, pompage de l'eau, sécurité alimentaire

Dedicate

“This thesis is dedicated to my lovely Family and my surrounding, who have always Believed in me, encouraged and supported me in everything I undertake”

This work is dedicated:

To my parents with love and gratitude,

To my Sisters and Brothers,

To my friends,

Thank you All for supporting, inspiring and encouraging me always throughout my research.

Thank you for your unconditional love and always taking care of me.

May Allah rewards you!

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Table of contents

List of figures

List of Tables

Abbreviations

AER: Agency of Renewable Energy

AMADER: Malian Agency for the Development of Domestic Energy and Rural Electrification

APV: Agrivoltaic or Agrophotovoltaic

AW: Annual Worth

BCR: Baenefit Cost Ratio

CEFA: Comitato Europeo per la Formazione e l'Agricoltura

CMDT: Malian Company of Textile Development

ECOWAS: Economic Community of West African States

ENEA: National Agency for New Technologies Energy and Sustainable Economic Development

FAO: Food and Agriculture Organization of the United Nations

GDP: Gross Domestic Product

HDI: Human Development Index

IEA: International Energy Agency

IRENA: International Renewable Energy Agency

IRR: Internal Rate of Return

OMVS: Organization for the Development of the Senegal River

ON: Office du Niger

PV: Photovoltaics

PV-GM: Ground-Mounted Photovoltaics

SDGs: Sustainable Development Goals

SOMAGEP: Malian Society for Drinking Water Management.

SSA: Sub-Saharan Africa

UN: United Nations

UNCSD: United Nations Conference on Sustainable Development

UNICEF: United Nations International Children's Emergency Fund

WEF: Water-Energy-Food

Chapter 1

1 Introduction

1.1 Context

Many initiatives have been multiplied around the world in recent years to promote the consumption of clean or less polluting energies. In Africa, most farmers still use diesel generators or electricity to run small scale farm's irrigation systems, this is due to lack of knowledge on the best green and economical choice of technology to be used to perform the same function (Randle-Boggis et al., 2021). The Agriculture shows an important role in Mali as in most Sub-Saharan economies. The consumption of renewable energy in Agriculture sector in Africa especially in Sub-Saharan Africa is highly needed in order to fight against food insecurity and extreme poverty.

Despite these initiatives of the powers and several African countries, pollution, climate change and desertification remain an obstacle in the direction to meet to economic and demographic development as well as to the constant energy demand increasing. In Africa, access to clean energy, water and food security is very low, particularly in sub-Saharan Africa and even lower or inexistent in remote regions not connected to the electricity grid. The region continues to be affected by poverty and food and nutrition insecurity at national and household levels (Mabhaudhi et al., 2016).

The challenges of rural electrification for universal access to electricity in Africa, clean and fresh water accessibility and food security are considerable. Today, 1.1 one billion people do not have access to electricity in the world, 87% of which is in rural areas; they are 600 million in sub-Saharan Africa (Boyé, n.d.). Despite its enormous potential in renewable energies: hydroelectricity, biomass (often overexploited), wind, and, of course, an important solar energy resource in most regions. The electrification of sub-Saharan Africa is a priority, to ensure sustainable economic development, access to water promoting economic activities and finally ensuring food security. It can be done by extending the grid or by setting up mini-grid or off-grid solutions using renewable sources.

Climate change, demographic development and geopolitical tensions that are already affecting the Mediterranean region may become more severe in the future (Marocaine, n.d.). The combined effects of desertification, biodiversity loss, water scarcity, groundwater depletion in extensive areas of the region and the rise of extreme weather conditions are likely to put further strain on agricultural, food and energy systems in the SSA region. These looming threats call for better coordination of sectoral policies and enhanced regional collaboration in the deployment of WEFE Nexus solutions addressing the specific challenges of the region.

1.2 Problem statement

The low share and the underdevelopment of Water-Energy-Food for renewable mini-grids to ensure electricity and water accessibility for economic development in Africa especially in West African is non-existent. Water-Energy-Food nexus can be employing at high level of efficiency in the development in Sub-Saharan Africa (SSA). As a case study for further development of the sector, the business case for agrophotovoltaics will be investigated, with a focus on the SSA region. The state of the art for installation combining PV installations with cultivations and livestock will be analyzed, along with the market potential and a case study analysis.

In a country like Mali, access to electricity is low especially in rural areas. The population growth and industrial development increase the energy demand. The environmental friendly, affordable, reliable solutions are needed to meet this demand growing, provide clean water for irrigation to ensure food security. Water-Energy-Food integrated in business models is inexistent in Mali yet or the agrophotovoltaics systems can be the best solutions for decentralized energy and water demand, provides the agricultural activities for food security and economic development without pollute the environment.

Agriculture has become one of the reasonable economic sector in Africa, being the source of income through cash-crops and food-crops cultivation this sector faces difficulties due to lack of water mostly and it rains seasonally, in rural areas as well as lack of environmental and economical friendly technologies of pumping water from the surface or underground water source to the farms for irrigation, in some cases small farms are most vulnerable due to the rise of diesel prices to run the generator for irrigation (Mabhaudhi et al., 2016), this mainly occur in areas where there is a growing use of butane gas for irrigation purposes. The access to clean and reliable energy and water supply for rural areas in Koutiala is still a major problem (Seidou et al., 2020), to ensure the achievement of sustainable development goals in energy and water supply. Agrophotovoltaic system can provide irrigation at the full time of year not only at rain season.

1.2.1 Research objectives

1.2.1.1 Main Objectives

The main objective of this thesis is to find suitable, cost-effective, clean and environmentally friendly solar solutions to respond to the Water, Energy and Food insecurity for people living in Koutiala (Mali).

1.2.1.2 Specific objectives

The specific objectives are to:

- ✓ Estimate the electricity and water demand of the community for their activities;
- ✓ Assess the renewable energy resources in the area that could support the development of the agrophotovoltaic system;
- ✓ Perform a technical assessment of the agrophotovoltaic system to meet the demand estimated above;
- ✓ Perform an economic assessment of the agrophotovoltaic.
- ✓ Integrate the system in business models with cost-efficiency.

1.3 Research Questions

I. What are the ways to develop the use of energy in water accessibility using in food processing in Koutiala?
II. What are the policies to manage nexus?
III. How can we improve the water and energy efficiency by using renewable energy resources?
IV. How can we do the cost-efficiency analysis of the Water-Energy-Food integrated business models for renewable mini-grids in national and international scale?
V. How to integrate it in the business? Are these business models profitable?
VI. What will be the recommendation regarding this business model?

1.4 Working Hypothesis:

The renewable energy for water accessibility using in food processing integrated in business models taking in account the environmental exigency, cost-effective, is the most desirable scenario for the development of renewable energy installations in Koutiala.

1.5 Relevance of the study

Sub-Saharan Africa (SSA) has the lowest energy access rates in the world. Electricity reaches only about half of its people, while clean cooking only one-third; roughly 600 million people lack electricity and 890 million cook with traditional fuel (IEA, 2018). Exploitation of renewable energy resources like Biomass, solar, wind can provide enough energy for these people. The use of solar and wind for water pumping can improve water access and water efficiency. Solar energy is used in wastewater treatment and then this water is used for agriculture, food processing for the business. The renewable energy for Water-Energy-Food security is environmentally clean. Agricultural value chains can greatly benefit from access to renewable energy sources in terms of agricultural productivity, reduced agricultural waste, and added value. Starting from existing experiences and practices in the world, it is possible not only to improve the current experience, but also replicate a successful model in the wider context of SSA.

1.6 Tentative Thesis Chapter Outline

The remainder for this study is structured as follows: In chapter 2, a brief review of the literature, it is about the historical background of the Water-Energy-Food nexus. The Water-Energy-Food nexus management method, the energy and water integrated in agriculture and food processing in the study area, in the purpose of the achievement of the Sustainable Development Goals (SDGs) of the agenda 2030. Deals with the state of the art of agrophotovoltaic installations, at a global level but with a strong focus on the SSA region. In chapter 3, we represent the methodology for the case study analysis, including the study area description, research design, data collection method, data analysis. In chapter 4, the result of the analysis and discussion are presented. This chapter highlights the management aspects of the water-energy-food nexus, their integration in business as well as the impact of their development on the environment. At the end, the chapter 5 is about the conclusion and the recommendations about the study.

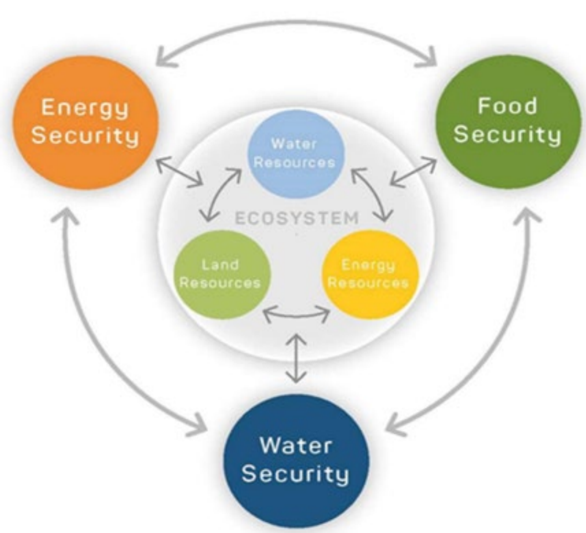
Chapter 2

2 Literature review

2.1 Water-Energy-Food nexus

The nexus approach is a somewhat ambiguous, but nonetheless conceptually useful perspective and is becoming popular over the years (Andrews-Speed & Zhang, 2019)**.**The linkage between subsystems is the theoretical core of the nexus approach, which argues that although subsystems such as, water, energy, and food can be analyzed independently, to do so would neglect the multiplicity of feedbacks and interdependencies that influence sustainable development that jointly affect the sustainability of the broader social-ecological system. The WEF Nexus model represents an innovative approach to sustainable development. The particularity of this new approach lies in its distinctive essence, since it promotes the concept of transformational engagement recently promulgated by the World Bank as the key tool to strengthen the impact of projects in terms of sustainable projects (Rasul & Sharma, 2016). Water, energy and food are critical resources for meeting the socioeconomic demands and sustainable worldwide economic development. Water, energy and food are essential for human well-being, poverty reduction. Global projections indicate that demand for freshwater, energy and food will increase significantly over the next decades due to population growth, economic development, urbanization, growing demand for food and diversified diets, climate change, resource degradation and scarcity (Res4Africa, 2019). The water-energy-food security nexus approach is an option for climate change adaptation. Already agriculture accounts for 70 percent of total global freshwater withdrawals, making it the largest user of water. They are inextricably interrelated; each of them significantly depends on others (Pappas et al., n.d.). The nexus approach begins by identifying two or more resources that are often broadly defined in terms of food, water or energy within a particular geographic or sociopolitical boundary. It then continues by quantifying resource use and the ways in which the use of one resource affects the other to affect the sustainability of the interconnected social-ecological system. Insular countries face challenges in maintaining adequate supplies for water, energy, and food demands (Pappas et al., n.d.), for example, consider the energy-water nexus in Texas, and focus their analysis on water used for energy and energy used for water. They find that energy production in Texas consumes enough water to provide for the needs of approximately 3 million people, while the energy used for water treatment could provide enough power for about 100,000 people (Res4Africa, 2019). Therefore, they argue for greater attention on the linkages between energy and water subsystems, and for the design of policies that account for their fundamentally interconnected nature. In response to this problem of overconsumption of energy and water, the use of renewable energy for nexus particularly solar photovoltaic energy to ensure the production of electricity and water treatment, pumping water for irrigation and economic activities of a given region (Randle-Boggis et al., 2021). Finally, to ensure energy, water and food security for sustainable development. Agrivoltaic co-locate crops with solar photovoltaics (PV) to provide sustainability benefits across land, energy and water systems. Policies supporting a switch from irrigated farming to rainfed, grid-connected agrivoltaic in regions experiencing groundwater stress can mitigate both groundwater depletion and CO2 from electricity generation (Conway et al., 2020). Whereas sub-Saharan Africa's (SSA) water scarcity, food, nutrition and health challenges are well-documented, efforts to address them have often been disconnected. Given that the region continues to be affected by poverty and food and nutrition insecurity at national and household levels, there is a need for a paradigm shift in order to effectively deliver on the twin challenges of food and nutrition security under conditions of water scarcity. There is a need to link water use in agriculture to achieve food and nutrition security outcomes for improved human health and well-being (Mabhaudhi et al., 2016).

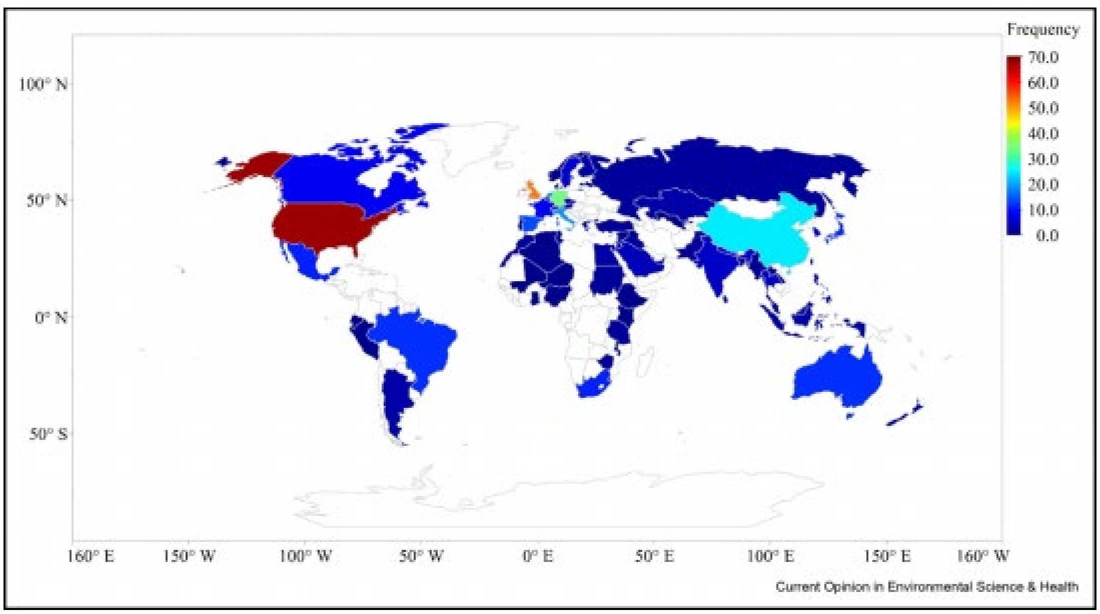
Figure 2.1: Water-Energy-Food nexus



Source: E3S Web of Conferences 183, 02001 (2020)

Food, energy and nutrition security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO, 1996). Over the past decades, issues of food and nutrition security have taken center stage in defining the development agenda in sub-Saharan Africa (SSA) and other developing regions. Significant funding has been channeled towards fighting food and nutrition insecurity. Although considerable progress has been made towards combating food and nutrition insecurity on a global scale (FAO, 2013), the same cannot be said for SSA. At 23.8% (FAO: Rome, Italy, 2014), the region still has the highest prevalence of undernourishment in its population. Most countries in SSA are still characterized as food and nutrition insecure. Therefore, despite achievements realized over the period under review, food and nutrition security remain as a major challenge (Chivenge et al. 2015).

Figure 2.2: Geographical representation of water–energy–food nexus project across countries



Source: Bibliometric analysis of water–energy–food nexus (www.sciencedirect.com)

It is observable in Figure 2.2 that water energy food nexus project can be categorized under regions, namely Europe totaling (46.7%), Asia (20.9%), North America Europe (17.9%), Africa (7.4%), South America (3.9%), and Oceania (3.2%). Top 10 countries with the highest nexus project include the United States (78 projects), the United Kingdom (53), Germany (38), China

(25), Italy (19), the Netherlands (19), Spain (14), Lebanon (13), Australia (12), and Brazil (12) (Samuel Asumadu et al. 2020).

2.1.1 Energy

Notwithstanding the role of energy being the lifeblood for human development, a big number of African populations remain without access to electricity. In spite of the progress in the last few years, the electrification rate in sub-Saharan Africa is currently just 43% (IRENA, 2013). According to the IEA report by 2030, roughly 600 million of the 674 million people without access to power will be in Sub-Saharan Africa, mostly in rural areas (IEA, 2017). Existing high growth of population and industrialization conduct to the exponential rising of energy demand and at the same time, to the high consumption of fossil fuel as a source of energy (Favretto, Dougill, Stringer, Afionis, & Quinn, 2018), which increases the green gas emission in the atmosphere and results into climate change hazards.

2.1.2 Water

Africa arises from or intersects with water issues (Caterina Brandoni et al. 2016). According to the World Health Organization, over 40% of the population in Sub-Saharan Africa do not have access to safe drinking water. Water is not only scarce, but also of poor quality; 45% of the population only have access to adequate sanitation facilities. Indeed, 30% of people only gained access to improved sanitation in recent years. Water is used for agricultural production and along the entire agro-food supply chain, and it is used to produce, transport and use all forms of energy (FAO 2011a). The role of water in achieving food and nutrition security for improved nutrition and human health cannot be understated. Water is essential to food and nutrition security through its linkages with all aspects related to economic access to food **(**FAO: Rome, Italy, 2015). While the role of water in the provision of food and nutrition transcends many sectors, this review focuses primarily on the linkages between water and agriculture. Sufficient and quality water is critical for agricultural production and achieving food and nutrition security (Dias et al., 2020).

Options for increasing agricultural production to meet growing food demand include increasing (i) the amount of land in production; (ii) yield, through crop improvement, plant biotechnology, or other alternative methods; and (iii) output per unit of input (productivity) on existing land (Edgerton, M.D. 2009). Agricultural productivity in SSA is currently low and remains well below potential yields (Foden et al., 2019), for example, in Mali, most farmers cultivate only during the rainy season due to lack of capacity and water pumping systems for irrigation. The few who cultivate throughout the year use systems that are harmful to their environment.

However, there is a need to improve current levels of productivity on existing land. Poor rural farmers in sub-Saharan Africa cannot afford to purchase inputs such as fertilizers, chemicals and herbicides and/or do not have access to new water pumping technology to improve their productivity and ensure sustainable development (Schindele et al., 2020). The types of water source using in agriculture are shown in figure 2.3.

Figure 2.3:Water sources using for irrigation

Source: Kids study zone: https://www.youtube.com/watch?v=iQZgNaU1iwA

There is a need to improve water productivity under rainfed production. This will benefit the majority of SSA's population (>70%) that relies on rainfed agriculture as the primary source of livelihood (Livingston, G. et al. 2011). Despite the limitations in resources suffered by farmers across SSA, there is high confidence that productivity levels can be improved (Nin-Pratt, A et al. 2011). Currently, yields in the USA and Europe are approximately 200%–300% higher than yields achieved in SSA (AGRA, 2013). The huge yield gap is partly due to poor agronomic practices and limited use of improved crop varieties in SSA. The USA and Europe also have higher water productivity (~2 kg/ m^3) compared to SSA (~0.2 kg/ m^3).

Figure 2.4: Electric pump bringing water from deep underground in India

Source: Schindele et al., 2020

2.1.3 Food

Food insecurity and malnutrition are problems that are currently affecting nearly every country in the world although it is more prevalent in SSA (Emmanuel & Napoleon, 2019). The fight against food insecurity and malnutrition must focus on the nutritional value and quality of agricultural products and diets, and increasing production using new methods and technologies, as most nutrients come from crops. Considering the United Nations' proposed SDG 2 (End hunger, achieve food security and improved nutrition, and ensure sustainable food production by 2030) (Seeliger et al., 2018), it is clear that while the "more crop per drop" approach addresses ending hunger and achieving food security, it is silent on issues of nutrition. It is directly linked with increasing food availability and access while silent on utilization, hence, ultimately failing to achieve sustainable food production. Sustainable food production describes the capability of agriculture over time to provide sufficient and nutritious food at all times in ways that are economically efficient, socially responsible, and environmentally sound (Sarkodie & Owusu, 2020). While there has been much effort towards combating food and nutritional insecurity, the balance has been tilted more in favor of food production than nutrition. The concept of "food and nutrition security" in itself may have unintentionally led to the two being treated as separate, with more focus on food production. The fact that agriculture underpins rural livelihoods and is inextricably linked to rural development explains why, over the past decades, large investments have been made in agriculture.

2.2 Case study of Mali

Mali is a large landlocked country in West Africa with 1.24 million square kilometers (480,000 square feet) of land area. It lies between latitudes 10° and 25°N, and longitudes 13°W and 5°E. Mali is bordered by Algeria to the north, Niger to the east, Burkina Faso and Côte d'Ivoire to the south, Guinea to the south-west, Senegal and Mauritania to the west (See Figure 2.5 below). With 20.93 million inhabitants (2020), the density of the population is 16.79 inhabitants / km^2. Demographic growth rate is about 3.36%/year. The GDP of the country is about 17.280 milliards $USD (2019), with GDP/ capita of 879 $USD (2019) (World Bank, 2020).

About 90% of the people in Mali live in the southern region with the Niger and Senegal rivers, far from the Sahara Desert (Energy et al., 2011). The climate is highly variable and characterized by a long dry season and a rainy season averaging one month in the north and up to five months in the south. Rainfall ranges from 200 mm/year to 1,200 mm/year and has resulted in the climatic stratification of the country into four ecological zones with a highly diversified agricultural potential. Mali is highly vulnerable to climate change, climate variability and desertification. These factors may create risks for rural energy (RE) sector, affecting biomass production and hydroelectric resources. A large part of electricity production comes from large-scale hydropower produced on the Senegal and Niger rivers. Agricultural is the major source of income for more than 80% of the population (AfDB, 2015), it is practice in Rural and decentralized areas. Despite his large land usable for agriculture and irrigation, the food insecurity exists and is a major issue in the country due to the irregularity of rain water, lack of the policies and new techniques to improve agriculture and irrigation. The primary energy supply in Mali is biomass, supplying 78% of all energy consumed. While the official language of Mali is French, 80% of the people speak Bambara. Electricity access rates are low but improving at 55% in urban and 15% in rural areas in 2015 (REN21, 2015).

According to Mali's population projections from July 1, 2010 to July 1, 2035, the estimated in 2013 at 16,872,000 inhabitants, will increase to 20,913,000 inhabitants in 2020, 50% of whom will be rural. 2020, of which 50% will be rural (PDA, 2013). (see other details in Table 2.5).

Figure 2.5: Map of Mali

Table 2.1: Key indicators for Mali

Country name	Mali
Area	1.24 million km^2
Population	20.93 million inhabitants (2020)
Population density	16.79 inhabitants / km^2
Demographic growth rate	3.36%/year
Energy production	2.175 billion kWh
Energy consumption	2023 billion kWh
Electricity access	38.2% (2016)
CO_2 emission from energy consumption	800.000 Mt
GDP	17.280 milliards $USD (2019)
GDP/capita	879 $USD (2019)
GDP growth rate	4.8%(2019)
Illiteracy rate	31% (2018)
Official language	French
Money	Franc CFA (XOF)
HDI	0.434 (2019)

Source: https://www.populationdata.net/pays/mali/

2.2.1 Energy sector in Mali

The energy sector in Mali, still largely dominated by biomass, is in transition. The biomass, particularly wood energy, the main source of household energy, comes from the country's forests, whose capacity is estimated at nearly 31 million hectares, or about 25% of the country's surface area, accounted for 78% of total national consumption of the national energy balance in 2014, followed by hydrocarbons for 18% and electricity for electricity for 5%. All hydrocarbons for consumption are imported. In view of deforestation, energy dependence on hydrocarbons and the government's commitments in favor of renewable energies, a transition is necessary to provide an adequate response to growing energy needs (MEE, 2019).

This overconsumption of wood products (6 million tons in 2002) creates too much pressure on forests and accelerates desertification.

A draft national energy policy was approved by the Council of Ministers on 29 March 2006. It should notably allow:

- ✓ Reduce the share of wood fuel in overall consumption from the current 81% to 70% in 2010 and 60% in 2015
- ✓ Secure and increase the country's electricity coverage from 14% in 2004 to 45% in 2010 and 55% in 2015
- ✓ Increase the share of renewable energy in the national electricity production from less than 1% in 2004 to 6% in 2010 and 10% in 2015 (Council of Ministers on 29 March 2006).

Interesting initiatives for the use of biogas and improved stoves are taking place in order to meet the energy needs of the population while preserving wood resources.

In 2015, the rate of access to electricity in Mali was 55% in urban areas and 15% in rural areas (Isabelle Mayault, 2017). To promote rural electrification, the Ministry of Energy and Mines created the Malian Agency for the Development of Domestic Energy and Rural Electrification (AMADER) (Panapress 23 janvier 2006**)**. According to the OECD, 80% of Mali's electricity was supplied by hydroelectric plants and 20% by thermal plants in 2006 **(***Jeune Afrique* du 11 juin 2006). Solar energy accounts for 3.1% of Mali's electricity consumption. Solar energy represented 3.1% of the national energy mix in 2015, a share that has been increasing since zero in 2012, thanks in particular to private initiatives (Isabelle Mayault,2017). Growth in electricity demand is mainly driven by domestic consumers, industrial and the mining sectors. The national grid has a large but declining share of hydroelectricity which accounts 44.4 % of all electricity produced in 2014, with the rest from fossil fuel powered plants. Specific domestic energy policies are being addressed by the state and by the rural and domestic energy agency (AMADER, 2014).

Major power cuts continue to occur in the months of May and June, when dams have not collected enough water. Several cities and the capital are without power for several hours a day. This is particularly damaging for industries and services.

In April 2021, Mali's Minister of Mines, Energy and Water, Lamine Seydou Traoré, deplored the dilapidated state of the energy debt system in Mali. He envisaged heavy investments to rectify the situation (EDM SA, 2021**).**

The Malian electricity sector can be divided into four segments: the interconnected system, isolated centers, captive generation by large consumers and the rural sector.

The implementation of the various projects and programs has led to the following key indicators (Rapport SIE, PDIO, 2015) for the energy sector (as of 2014).

Table 2.2: Indicators of energy sector in Mali

Variables	**2012**	**2013**	**2014**	**2015**	**2016**
Electricity access rate	31.7 %	32.4%	34.9%	35.7%	38.2%
Urban electricity access rate	64.1%	66.8%	70.7%	79.5%	88.6%
Rural electricity access rate	17.8%	17.2%	17.4%	16.7%	19.9%
Average tariff for low voltage electricity, perimeter EDM	100	105.2	105.6	105.4	104.2

SA (urban center) excluding TVA in FCFA					
Average electricity tariff in AMADER's areas of operation in F CFA	245 < and < 300				
Electricity production EDM SA (Gwh)	1276	1420	1574	1594	1768
Share of non-hydro RE in electricity production			7%	7%	ND*
Consumption of petroleum products per year (TOE)	911839	972928	1024000	1056864	1373533
Butane gas consumption in tons	13279	12010	12228	12982	14530
Biomass consumption	78% of the national energy balance 2014			71.6%	73.2%
Import of all hydrocarbon consumption	17% of the balance 2014			24.9%	22.3%
Electricity consumption	5% of balance 2014			3.5%	4.6%

Source: Rapport SIE, PDIO, 2015

The electricity sub-sector contributes 1.91% of GDP (DNTCP/MF, 2010). The oil sub-sector accounts for 26% of total imports in 2010 and 22% in 2015. imports in 2010 and 22% in 2015, which makes it very sensitive to price volatility.

Energy dependence on hydrocarbons remains high and presents price and availability risks and availability due to the country's landlocked nature. Despite significant hydraulic and solar potential, the share of thermal power reached 42.1% of total production in 2016 and EDM SA's thermal generation fleet of EDM SA is outdated, resulting in an expensive cost of production per kWh cost per kWh;

The high cost of thermal generation in Mali and the government's desire to reduce dependence on oil products. The high cost of thermal production in Mali and the government's desire to reduce dependence on petroleum products opens up interesting prospects for renewable energy based on national resources, which is a renewable energies based on national resources, solar, wind, hydraulic and biomass.

EDM-SA currently provides electrical energy from three different electrical systems that are not interconnected with each other, namely: the interconnected network (RI), the isolated centers (CI) and the interconnection with Cote d'Ivoire.

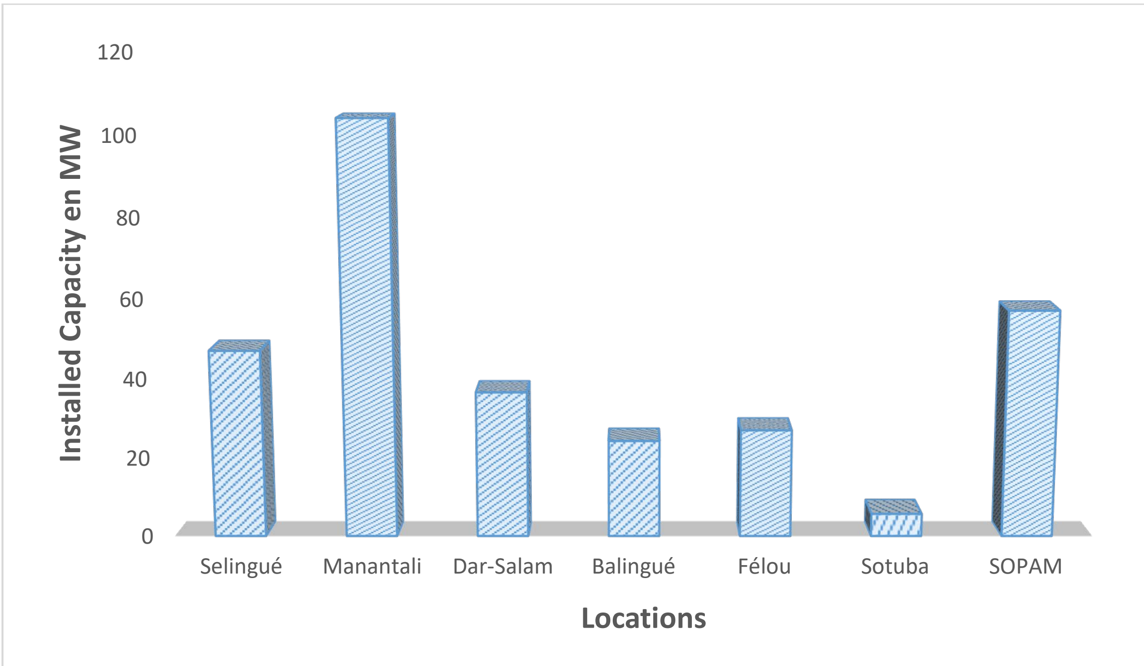
Thus, in 2017, EDM-SA's electricity supply was characterized as follows: **(**Données extraites du rapport d’activités d’EDM-SA 2017):

The interconnected system of Bamako which is composed of:

Five EDM-SA power plants: The Sélingué hydroelectric power plant (47 MW), the Sotuba hydroelectric plant (5.7 MW), the Dar-Salam thermal plant (36.6 MW), Balingué thermal power plant (24.32 MW); the Manantali hydroelectric power plant (within the framework of the OMVS), of which Mali's share is 104 MW, i.e. 52% of the total installed capacity); the Félou hydroelectric power plant (within the framework of the OMVS), of which Mali's share is 27 MW, or 45% of the total installed capacity); the 56 MW IPP SOPAM thermal power plant, initially operated by the independent producer SOPAM was taken over by the State and operated by EDM-SA under the name of Sirakoro thermal power plant. Sirakoro thermal power plant. It is shut down as of May 2017;

The rental thermal power plants recorded a cumulative capacity of 128 MW (which Aggreko Darsalam and Balingué for 78 MW, SES à Sikasso and Koutiala for 20 MW et Aska Enerji for 30 MW).

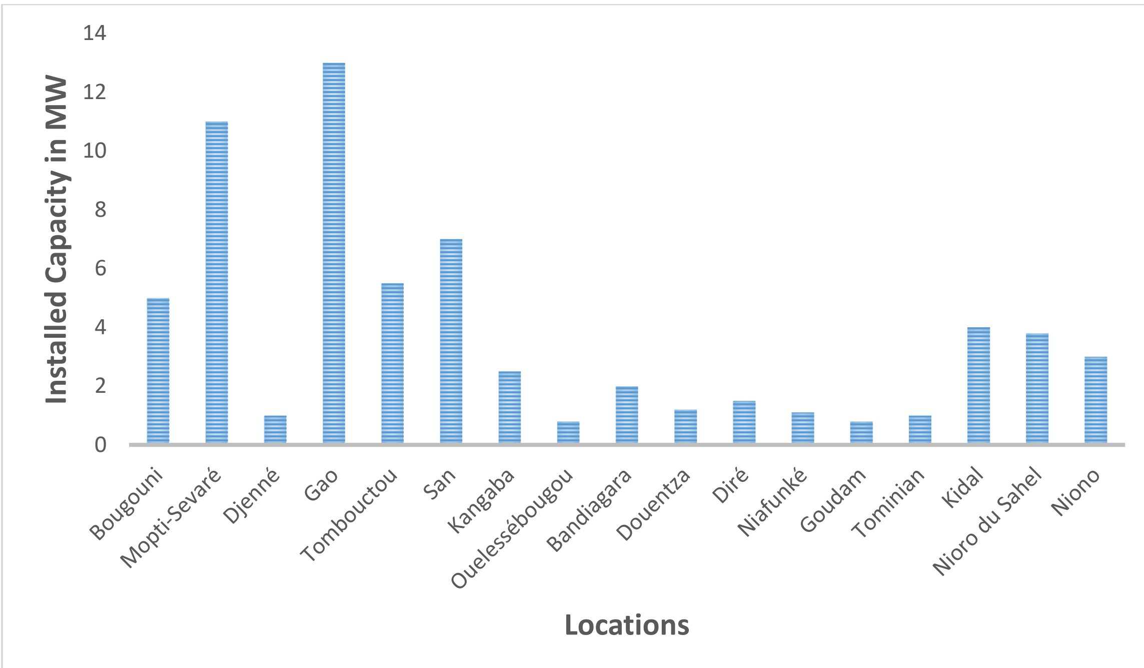
Figure 2.6: Capacity installed in Grid-connected electricity generation power plant in MW 2016



Source: EDM-SA, 2017

Hybrid renewable energy mini-grid power or off-grid power generation system that is fueled by one or serval renewable energy sources and distributes powers through a local grid network (Yadoo &Cruickshank., 2012). Mini-grids and off-grid systems can be cost-effective solutions for increasing the access of rural populations to electricity and for remote areas and can further reduce the negative impact of unreliable central grid services (REN21, 2015) ensuring more reliable energy supply and energy security for these remote areas. In Mali, small towns outside the existing and planned grid are categorized as included in the rural electrification programme under the responsibility of the Malian agency for the Development of Household Energy and Rural Electrification (AMADER). Access to affordable energy supplies and services can have a tremendously positive impact on rural development and social and economic opportunities for the poor and isolated communities. Rural electrification uses a mix of diesel and PV. About 10% of rural energy services are provided using RE, including mainly small-scale applications such as Solar Home Systems (SHS) (AfDB, 2015).

Figure 2.7: Off-grid electricity generation plants MW (2016)



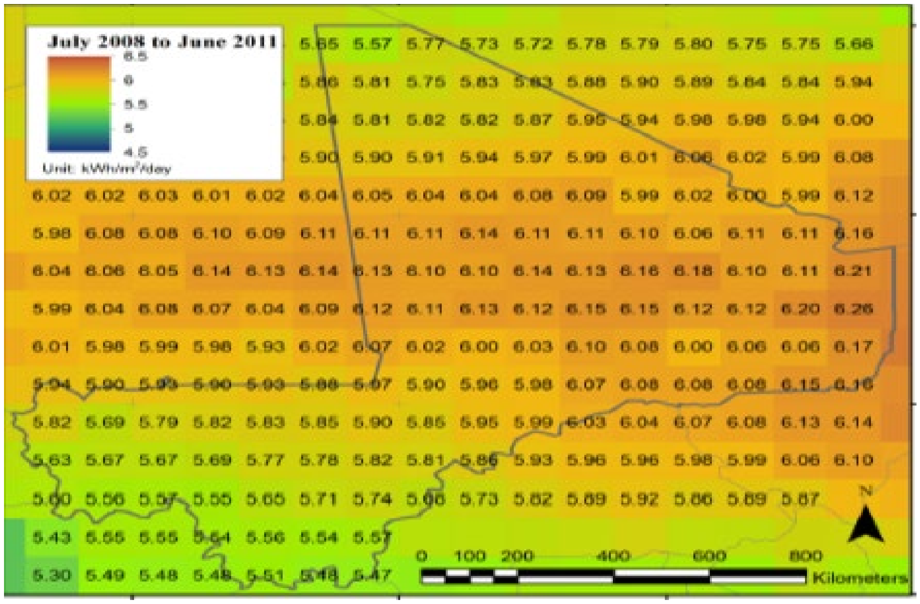
Source: EDM-SA, 2017

2.2.1.1 Renewable Energy Resources in Mali

2.2.1.1.1 Solar

The solar irradiation is very important and distributed on the whole national territory. It reaches on average 6 kWh/m2 /d for a daily sunshine duration of 7 to 10 hours. Solar is already used for electricity generation. In 2015, about 1Ktoe of electricity had been generated by solar (AFREC, 2016) as shown the figure 2.8 below:

Figure 2.8: Solar radiation across the country



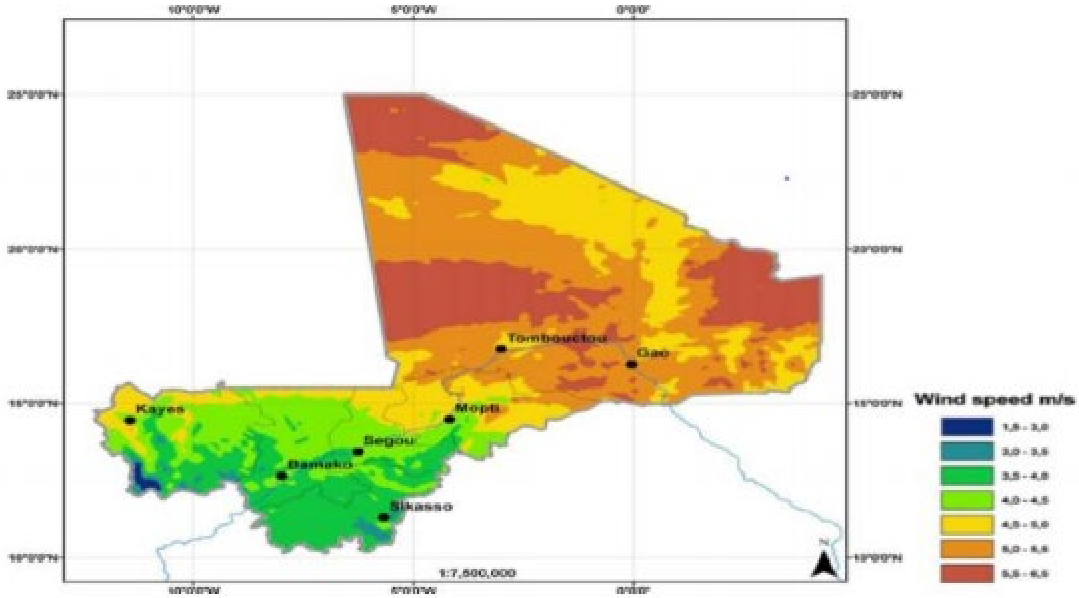
Source: REA, 2017.

According to information from AER, more than 800 solar pumps providing drinking water and more than 70,000 Solar Home Systems (SHS) had been installed in Mali by 2007. In addition, numerous installations power villages and infrastructure such as dispensaries and schools, while more than 1000 kWp has been installed for telecommunication amplifiers and a non-quantified but smaller number of solar water heaters and solar dryers. Exploitation of solar energy is expected to increase significantly in the years to come due to the reduction of solar energy equipment prices (panel, batteries inverters converter etc.) and also the decline of oil reserves and the increase oil prices. Likewise, solar PV is expected to fulfill the need to provide electricity to village infrastructure such as water pumps, dispensaries, schools and administrative buildings in non-electrified villages and to provide electricity in terms of SHSs for people living in dispersed settlements and on the outskirts of electrified villages (Nygaard et al., 2010). AMADER uses solar PV-diesel hybrid systems for most rural electrification projects (AMADER, 2015).

2.2.1.1.2 Wind

The potential of the Wind energy varies considerably across the country. With the speeds range from the lowest 2m/s to the highest 7m/s. as shown the figure 2.9 below:

Figure 2.9: Wind speed across the country



Source: REA, 2017.

There have been attempts to establish wind power in Mali, but so far wind is only exploited in a few water pumping installations for agricultural and domestic purposes. Mali's wind energy resource is concentrated in the central and northern parts, from Mopti northwards, where average wind speed of about 3 m/s to 7 m/s is found in large areas.

2.2.1.1.3 Hydro

The exploitable potential identified is 1,150 MW on about twenty sites with a corresponding average annual production of approximately 5,600 GWh. So far only 180 MW have been exploited (IRENA Statistic, 2017). Currently, nearly 840 MW of this potential remain available, undeveloped. The existing power plants include the Selingue on the Sankarani river, an offshoot of river Niger, and the Manantali, Gouina and Felou plants on the Senegal River. The manantali dam provides the electricity for Mali, Mauritania and Niger.

2.2.1.1.4 Biomass energy

Fuel wood is the main source of household energy supply in Mali. Country's forestry potential is estimated at roughly 33,000,000 hectares, including a standing volume of about 520,000,000cubic meter (m^3). However, these forests are under pressure as the deforestation rate yearly is estimated at 4,000 square kilometer (Km^2) (AFREC, 2016**).** As an agricultural country, Mali possessed other forms of biomass that could be used for energy supply include biofuel from jatropha plantations and agricultural waste such as bagasse form sugarcane, cotton stalks and rice straw. Since 1997 the overall yearly production capacity of alcohol is estimated to 2,400,000 liters and jatropha plantation for about 2000 hectares (AFREC, 2016).

2.2.2 Water sector in Mali

The problem of water resources is essential and even vital for the populations in the Sahel zone particularly in Mali. Indeed, the decrease in rainfall, repeated droughts, demographic pressure and unsuitable production techniques have led to a profound ecological imbalance, with the aggravation of certain phenomena such as the destruction of aquatic habitats, wind and water erosion and water erosion, various pollutions resulting from polluting discharges in aquatic environments, etc. In some regions of the country, conflicts between various uses of water, appear because of the fall of water tables, the early drying up of water bodies and the shrinking of productive spaces.

Water supply and sanitation in Mali faces significant challenges. Poor water quality leads to potentially lethal diseases. In 2018, the Ministry of Energy and Water reported access rates to drinking water of 65.3% in rural areas, 74.7% in urban areas, and 68% national wide (Abdoulaye Faman Coulibaly 2018).

The Ministry of Energy and Hydraulics is responsible for drinking water supply. Water sanitation is mainly the responsibility of the Ministry of Environment, Sanitation and Sustainable Development, while hygiene promotion is the responsibility of the Ministry of Health and Public Hygiene.

Over the past ten years, and based on the "National Water Policy" document adopted in 2006, significant progress has been made in terms of the water sector's contribution to the country's development. Despite these important achievements, the results are mixed. Indeed, a large part of the population, especially in rural areas, still does not have access to drinking water within a reasonable distance, sanitation in urban areas still falls far short of the population's expectations, food security is still a concern for the public authorities, and water resource management is still not carried out effectively.

It should also be noted that over time, the country's development context and challenges have evolved and many important changes have taken place over the years. On this point, we must mention among others: (i) the high level of poverty among a significant portion of the population; (ii) the important issue of climate change, which seriously affects development policies and threatens; (iii) the important and growing pressure on natural resources, including water; (iv) the disengagement of the State from production activities and its refocusing on its regalia missions; (v) the decentralization process, which entrusts various competencies to local authorities; and (vi) the existence of a sub-regional dynamic for transboundary water management.

This global context, coupled with the need to take into account changes at the international level related to the water resources policy in West Africa, the African Union's Agenda 2063 and the Sustainable Development goals (SDGs) by 2030, fully justify the updating of the "National Water Policy" document National Water Policy" adopted in 2006. The absence of a forward-looking vision of the contribution of the water sector to the country's sustainable development will be a definite handicap due to the cross-cutting nature of water in the country's various development sectors.

According to the Société Malienne de Gestion de l'Eau Potable (SOMAGEP), the rate of access to drinking water was close to 100 percent in the capital city of Bamako in 2016, compared to about 60 percent in 2014 and 70 percent in 2015 (RFI,2018). However, the city, which is capable of supplying 200,000 cubic meters of drinking water per day, reportedly faces a demand of about 250,000 cubic meters (RFI,2018) of drinking water per day, would face a demand of about 250,000 m^3. Following a contract signed with Mali's Minister of Economy and Finance Boubou Cissé in June 2017, the European Investment Bank is planning €50 million to double the city of Bamako's drinking water production capacity "from 144,000 to 288,000 m^3 per day (Jeune Afrique, 12 juin 2017).

In the north of the country, drinking water is mainly provided by local facilities (RFI,2018). In the regions of Timbuktu and Gao, more than half of the inhabitants consume water from sources at risk of bacteriological contamination (eda.admin.ch, 2014).

In 2012, the insurgency by armed groups in the north of the country degraded the operation of water facilities in the cities of Timbuktu and Gao (AFD). The presence of Malian military and armed groups in the north of the country has led to the deterioration of the water system. The presence of Malian military and large numbers of displaced people in Mopti has put great pressure on the city's water resources.

In April 2019, UNICEF is releasing 385 million CFA francs (approximately 580,000 euros) for a project to provide drinking water to 20 schools and 12,000 villagers in the Gao region. Irrigation and agriculture in the country are provided by rainwater, rivers and lakes.

2.2.3 Agricultural potential in Mali

Mali has significant agro-sylvo-pastoral and fisheries potential, but is unable to fully cover its food needs and reach a fully cover its food needs and achieve a satisfactory and sustainable level of food security satisfactory and sustainable level of food security (Samake Amadou, Bélières Jean-François, Bosc Pierre-Marie, 2007). Mali is a vast Sahelian country with an area of 1,241,238 km^2 (Samake Amadou, Bélières Jean-François, Bosc Pierre-Marie, 2007). The climate is very diverse, ranging from pre-Guinean to desert. It has a monomodal rainy season, the duration of which decreases from south to north. Thus, agricultural potential decreases from south to north, except in developed areas. The hydrographic network consists mainly of the Niger and Senegal rivers. Depending on the amount of rainfall and the availability of surface water, there are five agro-climatic zones in Mali, including the Saharan zone, the Sahelian zone, the Sudanian zone, the Sudano-Guinean zone and the Delta zone. Mali has a high potential for irrigated land thanks to the Manantali, Seuil de Talo, Sélingué, and Markala dams. Markala, placing Mali in the top ranks of ECOWAS countries in terms of water control. This shows the importance of the agricultural sector and the need for a good mechanization strategy for its rational use. mechanization strategy for its rational exploitation.

Mali's economy is essentially based on the agricultural sector, which employs nearly 80% of the active population and contributes 33% of the GDP and 15% of export revenues (PDA 2013). Agriculture contribute 36% of the PIB (World Bank,2020). The cultivable area is estimated at around 11,500,000 hectares, of which 2,000,000 hectares are irrigable (AFREC, 2016**)**, and the potential for livestock production is very important. Despite these enormous agricultural potentialities, it is important to note that Malian agriculture has been and remains uncertain because of irregular rainfall, the fragility of the soil, and the influence of the desert and Sahelian climates on the northern side. At the socio-economic level, there are a total of 800,000 farms of which approximately 700,000, or 86%, are engaged in agriculture, 100,000 farms are strictly livestock breeders or fishermen (RGA, 2005). Southern Mali, with more than 200,000 family farms, is the most important agricultural region, both in economic terms (cotton) and in terms of employment. The cotton sector alone affects the lives of about one-third of the Malian population.

2.2.4 Energy-Water in agriculture for sustainable development

Water, energy and food are essential for human well-being, poverty reduction and sustainable development. Global projections indicate that demand for freshwater, energy and food will increase significantly over the next decades due to population growth, economic development, urbanization, growing demand for food and diversified diets, climate change, resource degradation and scarcity (Hoff 2011). Already agriculture accounts for 70 percent of total global freshwater withdrawals, making it the largest user of water. Water is used for agricultural production and along the entire agro-food supply chain, and it is used to produce, transport and use all forms of energy (FAO 2011a). At the same time, the food production and supply chain consumes about 30 percent of total global energy (FAO 2011b). Energy is required to produce, transport and distribute food as well as to extract, pump, lift, collect, transport and treat water. The renewables energies sources are available in Sub-Saharan Africa and can be used in water supply, water treatment and subsequently be used for agriculture and other household tasks. Wind and solar photovoltaic systems are used for pumping groundwater or water from rivers and streams. In addition, solar photovoltaic (PV) systems are also used for water desalination. They are used to supply fresh water which is vital for people's well-being, and also to supply water for irrigation and agriculture to make good production for sustainable food security especially in rural and remote areas.

In Mali, the Office du Niger is a semi-autonomous government agency in Mali that administers a large irrigation scheme in the Ségou Region of the country. Water from the Niger river is diverted into a system of canals at the Markala dam 35 kilometers downstream of Ségou. The water is used to irrigate nearly 100,000 hectares of the flat alluvial plains to the north and northeast of Markala part of the Delta mort. Although the French colonial administration constructed the system to produce cotton for the textile industry, the main agricultural product is now rice. Around 320,000 tons are grown each year representing 40% of the total Malian production. The Office of Niger (ON) is cited as a case for assessing sustainable production in Mali because it is the most important rice-growing area in Mali where agriculture is done using water from the dam. After the rice harvest, onions are also grown in the area. Besides the massive production of rice on the Niger River, other small-scale agricultural activities such as gardening are carried out along the Niger and Senegal Rivers.

2.2.5 Some agriculture crops in Mali

The food crops in Mali are multiple: we have rice massively cultivated in the region of Segou (Office du Niger) on the Niger River, corn, cotton, millet, sorghum, potatoes, beans, massively cultivated in the region of Sikassa (south of the country). Vegetables such as carrots, tomatoes, okra, onion, lettuce, cabbage, etc. are generally garden crops.

2.3 Example of integrated investments targeting water, energy and food

2.3.1 Ikondo-Matembwe project (Tanzania) (Pasquale Lucio Scandizzo et al. 2019)

The project, as assumed by CEFA (Comitato Europeo per la Formazione e l'Agricoltura) covers an area of 8 villages, sited in five rural wards of Tanzania (Matembwe, Ikondo, Lupembe, Ukalawa and Kidegembye) in the Njombe Rural District. The total population of the area is 20,928 inhabitants, with an overall number of households of 4,435.

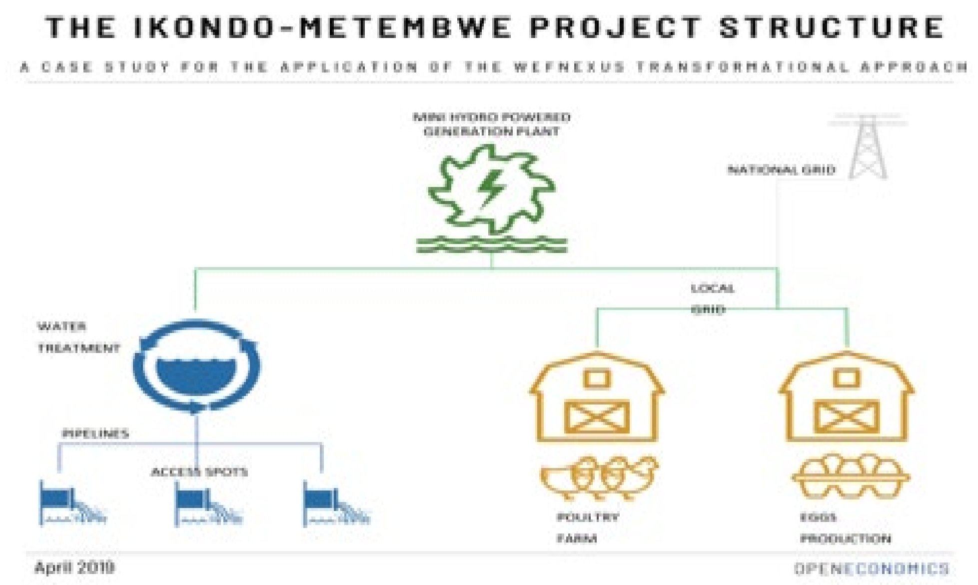
Within the Njombe Rural District people rely on farming, with agriculture being the largest sector of the local economy. A share of 67% of the households has a farming activity and agriculture is crucial for their food provision and living. Agriculture is also the main reason for income, especially through the cultivation of local harvests such as beans, tea or maize. Another important means of livelihood for the local population is livestock. Beef is the largest meat product followed by lamb/mutton in mainland, while chicken and pork are mainly produced in rural areas thanks to the lower prices of the meat.

Furthermore, Tanzania faces high environmental challenges because of unsustainable harvesting of its natural resources, unchecked cultivation, climate change and water- source encroachment.

Another criticality within the target area is access to water. Water supply and sanitation are poorly accessible to the population. Although the National Government has embarked on a major sector reform process since 2002, access to potable and drinking water is still difficult for local population as water points are poorly managed and far from main aggregation centers. A decentralization in the water supply has been carried out since the local government authorities and is carried out by 20 urban utilities and about 100 district utilities, as well as by Community Owned Water Supply Organizations in rural areas.

The Ikondo-Matembwe electric infrastructure is based on two interconnected hydro power plants that have a total generation capacity of 550 kW of electric supply and is able, through a local grid that currently counts 1,102 connections, to provide access to energy to the entire target population, approximately 890 households, 186 businesses and 26 public services.

Figure 2.10:Ikondo-Metembwe project



Source: Pasquale Lucio Scandizzo et al. 2019

In the Ikondo-Matembwe project area, the electricity activated by the hydro plant enables the increasing in the production of an animal feed factory and a poultry hatchery. This business and the related activities are fostered by the abundant and reliable energy supply that provides electricity, at a lower price and for a longer period of time of the former energy-generating solution, permitting an increase in agricultural and processing activities, such as poultry feeding and seed production.

2.3.1.1 Investment cost of the project

The total investment cost for the Ikondo-Matembwe project is USD 3,781,131 split in its components of energy, water and food/livestock according to the following figures:

Table 2.3: Energy Capex

Capex related to Energy components	$ USD	%
Project management and development- Human Resources (local)	110,880	3.8%
Project management and development- Human Resources (expat)	165,984	5.6%
Project management and development- Local transports	212,016	7.2%
Project management and development-Other	28,616	1.0%
Project management and development M&E activities	8960	0.3%
Supporting activities for local communities	66,696	2.3%
Legal and authorization costs	11,200	0.4%
Land purchase	8,400	0.3%
Generation plant and distribution line-Human Resources (local)	142,464	4.8%
Generation plant and distribution line-Human Resources (expat)	107,520	3.6%
Generation plant-Asset costs	1,246,168	42.2%
Distribution line-Asset costs	544,320	18.4%
Last mile connections-Asset costs	246,848	8.4%
Local Office costs	50,400	1.7%
TOTAL	2,950,472	100%

Source: Open economics elaboration on project Data

Table 2.4: Water Capex

CAPEX RELATED TO THE WATER COMPONENT	$ USD	%
Supporting activities for local communities	11,200	3.3%
Legal and authorization costs	5,600	1.7%
Pumping plant and distribution line- Human Resources (local)	77,952	23.1%
Pumping plant and distribution line- Human Resources (expat)	40,320	12.0%
Pumping & distribution pipe-Asset costs	202160	59.9%
TOTAL	337?232	100%

Source: Open economics elaboration on project Data

Table 2.5: Capex of Food

CAPEX RELATED TO THE FOOD COMPONENT	$ USD	%
Supporting activities for local communities	33,600	6.8%

Legal and authorization costs	9,520	1.9%
Land purchase	50,512	10.2%
Plant-Human Resources (local)	78,624	15.9%
Civil works and buildings-Asset costs	177,072	35.9%
Plant machinery and equipment-Asset costs	144,099	29.2%
TOTAL	2,950,472	100%

Source: Open economics elaboration on project Data

2.3.1.2 Operating and Economic Costs

The costs considered in the economic CBA were disaggregated following the investment costs for energy, water and food/livestock components. For the energy-related project, households pay an electricity tariff of 0.06 USD/kWh, public services pay a tariff of 0.043 USD/kWh and private business pays a tariff of 0.11 USD/kWh. Considering all the beneficiaries of clean energy due to the project, the total cost would be USD 742,406 in net present value for the entire project life. For the water-related activity, households would pay 0.0010 USD/litre after project implementation. Considering a consumption of 95.70 litres per day, the total cost would amount to USD 1,872,198 in net present value for the project lifespan. Regarding food /livestock activity, households would pay for livestock (poultry) and fodder. Considering a unit amount of USD 0.68 per animal and USD 21.35 per 50 kg of fodder, the total amount is USD 871,038 in net present value for the entire project lifespan.

The operating and maintenance costs refer to administration, audit and insurance, as well as ordinary and extraordinary maintenance. For the energy part, these costs are calculated at USD 396,253 for the entire project life; for water at 57,179 USD in net present value and for food/livestock at USD 395,029 in net present value.

2.3.1.3 The benefits produced by the Electrification components in the Project

Literature has extensively shown that there are several benefits from providing access to electricity supply in non-connected rural areas, such as: improvement in people's health, in education, in the productive processes of the communities, environmental benefits, as well as for the facilitation in communication. Electricity, furthermore, is a basic general-purpose technology that allows the productive usage of a large set of production techniques, including mechanization, irrigation and other modern inputs that are vital to agriculture. Electricity, therefore, plays a very important role in the social, economic and environmental life of the collectivity.

2.3.1.4 The benefits produced by the Water component in the Project

Water distribution is strictly linked to sanitation systems, and improvement in this sector brings to a decrease in potential environmental and health risks. The low percentage of Tanzanian population that has access to improved sanitation means that more than 50 percent of fecal waste is currently disposed without treatment, leading to contamination of groundwater and recurrent incidences of diseases such as diarrhea and cholera.

2.3.1.5 The benefits produced by the Food component of the project

Malnutrition is one of the most serious problem in many countries today, dramatized by its combination with other forms of poverty and the global inequality in food distribution. Malnutrition imposes high economic and social costs on countries and investing in improving nutrition is not only a crucial global mission but can also yield high economic benefits. Tanzania is estimated to lose Tsh 815bn (USD 512m) in yearly revenue from malnutrition which mainly decimates young children. A recent survey shows that about 69% of the Tanzanian children are anemic, 42% are stunted, 35% are iron deficient, 33% are vitamin A deficient and 16% are underweight (BMC Pediatrics,2017).

The main project benefits from enhanced food security can be summarized under the following headings: - Improved farmer's income from crop production benefits - Improved farmer's income from poultry and egg production - Nutrition and Food Security.

2.3.1.6 IKONDO-MATEMBWE PROJECT RESULTS

2.3.1.6.1 The Financial Cost-Benefit analysis

The purpose of the financial cost-benefit analysis is to assess the financial viability of the proposed project, testing whether the project is financially attractive for the investor or the investors involved. In the financial benefit-cost analysis, the unit of analysis is an individual stakeholder or a group of stakeholders and not the entire economy. In contrast, the economic cost-benefit analysis evaluates the project from the viewpoint of an entire (typically national) community.

The profitability of a project to the stakeholder considered is indicated by the project's Financial Net Present Value (NPV). A positive NPV indicates a profitable project from the point of view of the private party who has to undertake it, i.e. if the project generates sufficient funds to cover its cost to the stakeholder considered, including loan repayments and interest payments.

Table 2.6 below shows project revenues, project's investment costs and project net benefits for the entire project lifespan from the point of view of a private investor (a utility or a power producing company) that would own the energy producing asset:

Table 2.6: Project financial estimations

Project	Revenues Present Value $USD	Investment cost $USD	FNPV $USD
Energy	792,120	2,907,431	-2,115,311

Source: Open economics elaboration on project Data

Revenues are based on electricity sales and connection fees. Households are assumed to pay a tariff of 0.06 USD/kWh, social services of 0.04 USD/kWh and business of 0.11 USD/kWh. Connection fees for the base year are assumed to be around USD 128 and the national grid to be able to collect a tariff of 0.04 USD/kWh. Considering project data, the results of the financial Cost-benefit Analysis are negative, with a Net Present Value of USD -2,115,311.60 and an IRR of -4%. The IRR is also the discount rate at which the present value of the net benefit stream in financial terms becomes zero.

The results of the FCBA imply that from the point of view of the private stakeholder, which in this case is the utility owning the asset, the project is not feasible, as it will not be convenient for the investor to implement such a project in terms of profit. The financial gap, as highlighted within the data analysis, corresponds to 72% of the project CAPEX. Even though the project is not attractive from the point of view of the energy investor, it could be beneficial from the point of view of society at large. The Economic Cost Benefit Analysis (ECBA) can thus be used to ascertain whether the project would be beneficial from the broader point of view of the community involved and, more generally of the entire country.

2.3.1.6.2 The economic cost-benefit analysis of the project

To carry out the Economic Cost Benefit Analysis, two different scenarios have been considered for the three project's components: (i) simultaneous implementation and, (ii) implementation at different times. In the second scenario, the energy part alone is the main component with the major investment costs. This implies two distinct alternatives for water and livestock, consisting, respectively in the combination of (i) energy and water and (ii) energy and livestock. This scenario has been compared with an alternative case where all components are implemented together. The rational for this comparison is that energy is the activating component for the water supplied to the village, bringing about crucial economic benefits to the target population. In addition, energy is also the activating component of the livestock factor, as farmers need energy to improve their ability to use improved cultivation techniques. As per the livestock subcomponent, energy gives the opportunity to increase production through hatchery activities, through the use of electric equipment. This boosts productivity through an enhanced value chain and also improves the environment and the wellness conditions of the animals. In terms of project results, the Energy project alone ENPV turns out to be USD 5,940,652, while the Energy and Water project combination and the Energy and Food project yield respectively an ENPV of USD 10,651,791, and of USD 7,768,100. Therefore, the project with the highest Economic NPV is the integrated WEF Nexus Project, consisting of Energy, Water and Food, with an ENPV for USD 12,479,239. Simultaneous implementation of the three projects thus produces the largest impact in economic terms.

Table 2.7: Project Results

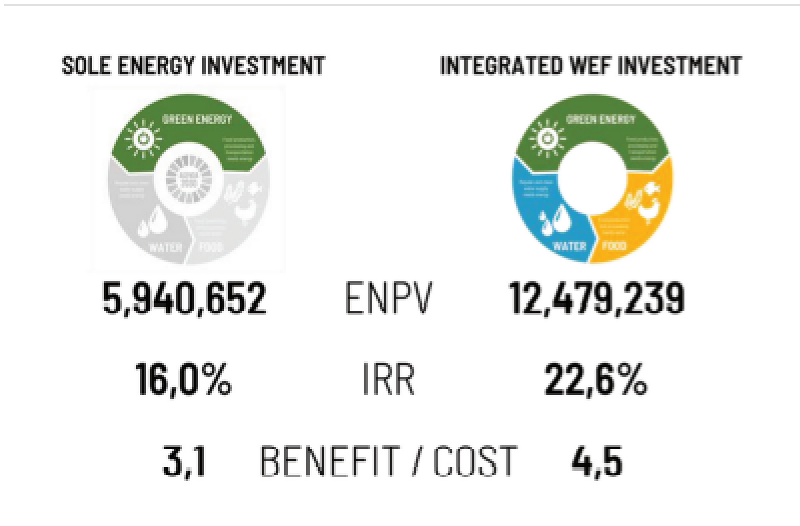
Project	Economic NPV $USD
Energy	5,940,652
Energy and Food	7,768,100
Energy and Water	10,651,791
Energy Water and Food	12,4479,239

Source: Pasquale Lucio Scandizzo et al. 2019

Although there appears to be only a small difference in terms of ENPV and economic benefits between the Energy and Water project and the complete Ikondo-Matembwe project, it must be considered that without Energy, the other two projects would not be adopted, as the investment costs would be much higher than those as assumed in the project. This is because energy is crucial for all activities and in the absence of the energy project component, it would have to be produced at much higher costs. This conclusion can be seen also through the lenses of a project expansion; the Energy project opens the possibility to further develop the Water and Food components. Further indicators of project performance are the Internal Rate of Return (IRR) of 16% with a Benefit Cost

Ratio (BCR) of 3,1 for the Energy project, and an IRR of 22,57% and a BCR of 4,5 for the Energy, Water and Food integrated project.

Figure 2.11: Energy and integrated investment IRR and cost-benefit ratio



Source: Pasquale Lucio Scandizzo et al. 2019

The BCR indicator is indicative of the peculiarity of the integrated project compared to the sole energy investment. The 1,4 points differential among the two projects has a clear explanation: energy is the enabler of the integrated project, if energy is not activated, the other two components would not be enabled. This is significant as in this case with a little investment quantified for the energy sector, it is possible to collect high benefits from the energy, water and food components. In addition, whilst the Nexus approach brings about mostly positive externalities, it is true that negative externalities might arise as well. If a positive externality is a benefit enjoyed by a third party, a negative externality implies a cost for the mentioned as result of an economic transaction. A traditional case of negative externality is the case of pollution, imposes costs on society and individual reducing, therefore the possible project benefits. The identification and quantification of these negative externalities and especially their conversion into monetary terms is important when evaluating the economic benefits and costs of a project although they are very difficult to compute. As per the WEF Nexus, negative externalities do not arise and the very few ones are not major negative externalities but only marginal ones. As per the mentioned, a kind of negative externality might be related to the reduction of diesel sales, brought by the switch undertaken by the project to produce energy from this conventional source into a RE based technology. Another externality that might be related to the project is related to the land expropriation and land right issue. Although it is a crucial advocacy aspect, it cannot be related to this project as it is assumed that those land that will be deployed to develop it are uncultivated, public lands with no economic value that will not affect neither farming nor farmers as agriculture is well known to be the main economic activity in rural areas.

2.4 Stat of art of Agrophotovoltaic installations

2.4.1 History

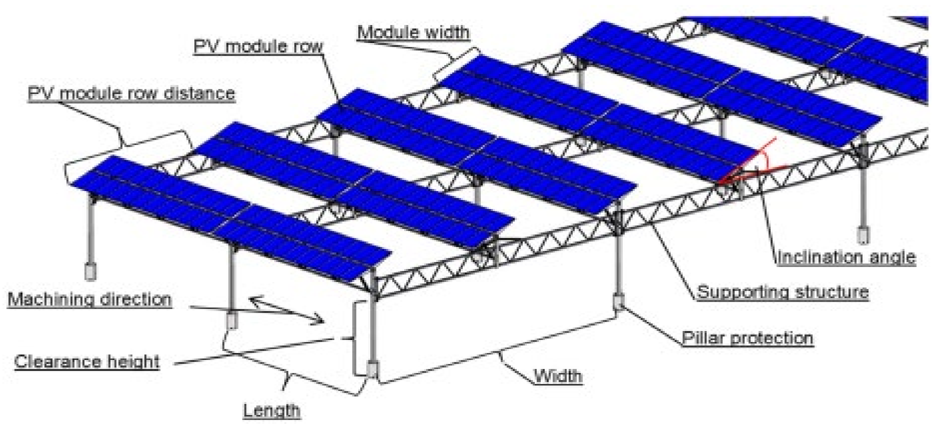
Globally, ground-mounted photovoltaics (PV-GM) have become the most cost competitive source of power generation (IRENA, 2018). Accordingly, PVGM represents a growing share in the PV marketplace (SolarPowerEurope,2018). Hardly discussed is the spatial aspect of PV-GM implementation, as well as the loss of cropland resulting from it. Land is the principal basis for human livelihood. It supplies food, fresh water and many other ecological resources. Yet due to socioeconomic development e.g. infrastructure, industrial estate and housing development as well as soil degradation and desertification, cropland is expected to decrease globally by between 50,000,000 ha (the size of Spain) and 650,000,000 ha (twice the size of India) by 2100 **(**IPCC, 2019). Consequently, cropland is becoming scarce. Accordingly, the availability of arable land per capita decreased by 48% between 1961 and 2016 due to the increase in global population (FAO.2019). Taking into account planetary boundaries **(**Rockström J, et al. 2009) and the limited availability of cropland, it can be foreseen that the rising demand for PV-GM will lead to increased land use competition and thus result in potential economic, ecological, political, and social conflicts in the future. One approach to meeting the challenge in terms of sustainable land use is the Integrated Food-Energy System, which enables the simultaneous production of food and energy on the same plot of land. Moreover, it utilizes synergetic effects by optimally exploiting the potential offered by both production systems, as seen for instance in agroforestry systems or agrofuel production with cascade use (FAO Books; 2014). One solution emerging from the PV sector for minimizing the impact of arable land grabbing is an agrophotovoltaic (APV) (IPCC ,2019), dual use of agricultural land, which was proposed for the first time by Goetzberger and Zastrow (Goetzberger A, Zastrow A, 1982). Since 2017, APV has been recognized as a strategy for avoiding or minimizing land impacts from PV systems in the Global Land Outlook, focusing on energy and land use by IRENA and UNCCD (Stephan Schindele et al.2020).

In Germany, a total of eight APV power plants have been in operation since 2004, three of which were built for research purposes. In parallel to the innovation process of APV in Germany, several APV pioneers have implemented demonstration projects, e.g. Japan 2004, Massachusetts (USA) 2008, Italy 2011, Malaysia 2015, Egypt 2016 and Chile 2017. Some advanced governments have already implemented APV dissemination policies, e.g. Japan, South Korea China, France, and Massachusetts**.** We estimate that approximately 2200 APV systems have been installed worldwide since 2014, leading to a capacity of about 2.8 GWp as of January 2020.

2.4.2 Technical parameters of APV system technology (Schindele et al., 2020)

The main technical parameters of the APV system technology are noted in Fig.2.12 and can be summarized as follows: The PV modules are elevated with a clearance height of 5 m so that the work of the agricultural machinery, in particular of the combine harvester, is not hindered by the APV power plant. The overall height of the installation reaches 7.8 m. Each individual unit has a width of 19 m, having been chosen to be many times the width of the machine most frequently used for this particular cropland. This ensures that as little area as possible is lost and reduces the additional work for the farmer to a minimum. Overall, the APV system takes up seven units in width, adding up to a total width of 133 m. The length of each unit is 13 m and was also chosen by a multiple of the farm’s most common machine, so that the farmer can process the field in both directions of the APV power plant in future. The power plant is two units long, resulting in a total length of 26 m. In order to ensure uniform crop growth, the APV installation must guarantee sufficient and homogeneous light distribution.

Figure 2.12: Fundamental technical parameters of APV system technology



Source: (Schindele et al., 2020)

2.4.3 Case study of Agrivoltaic

Agrivoltaic system is the agriculture combined with raised photovoltaic (PV) solar panels offer benefits for food, energy and water security, all on the same land footprint and avoiding vegetation removal and associated land degradation. Agrovoltaic systems (combination of biomass production and electricity production by photovoltaics (PV)) are typically installed in locations with high insolation and/or arid climates in order to protect the crops against drought and sunburn. Over the past decade, the studies to explore the performance of agrivoltaic have been developed over the world with experiments operated in France, Germany, Italy, the Netherlands, the USA, Chile, India, China, Japan, South Korea and Malaysia.

2.4.3.1 The Baofeng Group project of 1 GW in China (Reglobal)

Baofeng Group is in the process of expanding the capacity of a 640 MW solar park in the Binhe New District on the eastern banks of the Yellow River in the Ningxia Province to 1 GW. As part of this giant project, the company is combining PV power generation with the production of goji berries, which are an ingredient in traditional Chinese, Korean, Vietnamese and Japanese medicine. The Baofeng Group began managing 107 square kilometers of desertified land in the area 2014, and it initially planted alfalfa to improve the soil. The perennial flowering plant was then removed to enable the construction of the solar plants and, upon its completion, goji berries were planted underneath the panels. This helped resume goji farming in the region, which in turn revived an otherwise dead expanse of desert.

The first 640 MW section of the project, which relies on 13,000 Huawei smart string inverters, was grid-connected under China’s feed-in tariff (FiT) programmed for solar energy in 2016. The solar power plant is said to effectively reduce land moisture evaporation by between 30 and 40 per cent. The vegetation coverage has purportedly increased by 85 per cent while significantly improving the regional climate.

The panels were installed at a height of 2.9 m, which not only offers enough room for the cultivation of goji berries, but also ensures optimal operation and maintenance activities.

Figure 2.13: The Baofeng Group project of 1 GW in China

Source: Reglobal

2.4.3.2 Agrivoltaic in Sub-Saharian Africa

The agrophotovoltaic (APV) concept proposes the development of energy production systems based on photovoltaic solar technology, in harmonious and optimized combination with agricultural production in the most vulnerable regions to climate change as temperature increases and where land is a barrier. Mali and the Gambia are located in one of the most vulnerable regions to climate change as temperature increases are projected to be 1.5 times higher than in the rest of the world (Emmanuel Cheo). The promotion of food security has been a top priority in these countries. This has resulted in a push for more irrigated areas demanding the extraction of more water and energy for pumping water from groundwater and surface water. There has been an increasing scarcity of arable lands and in the upcoming decades in rural areas in Mali and The Gambia will face severe challenges resulting from climate change. Agrophotovoltaics is a sustainable energy system that provides food, water and electricity to the local population while increasing resilience of the agriculture sector against climate change. In this sense, the "Agrophotovoltaics for Mali and the Gambia: Sustainable Electricity Production by Integrated Food, Energy and Water Systems" (APV-MaGa) project aims at establishing Agrophotovoltaics as a sustainable energy system that provides food, water and electricity to the local population while increasing resilience of the agriculture sector against climate change (Emmanuel Cheo).

Additionally, the project seeks to prove the technical and economic viability of an integrated triple land use system and to gain a deeper understanding of synergies and interactions within the Water-Energy-Food Nexus in the partner countries and West African context. As per demand from the African partners, the five APV approaches will be exploited and suitable business models related to the local context will be tested.

2.4.3.3 Agrivoltaic in MENA (ENEA)

ENEA and RES4Africa Foundation are engaged to promote the development of agrivoltaic and green energy in the countries of the southern Mediterranean, avoiding conflicts linked to soil consumption, water, and food shortages. To respond to the problem of soil consumption for energy purposes which risks reducing the availability of food resources, ENEA will implement the task "Sustainable agriculture to favor the link between the main subjects involved in the design, construction and authorization of agrivoltaic plants, both from a cultural and landscape point of view, as well as from a technical and economic perspective.

2.4.4 In what Agrophotovoltaic is important in Malian's situation??

Mali has one of the lowest rates of access to electricity in the world, especially in rural areas. Most of the population does not have access to clean water, there is food insecurity in the country. But above all in an environmental context under pressure. These sectors are vulnerable to climate change. The combination of these being the lever of any development, it is clear that the agrivoltaic system will be a better solution to achieve food security, improve nutrition, and promote a sustainable agriculture.

The innovative Agrophotovoltaics (APV) system technology combines agricultural biomass and solar power production on the same site and aims at reducing the conflict between food and power production. Most of the APV in Mali are used for water pumping for irrigation and own electrification with a small scale. The APV is not developed in Mali and there are not government policies to implement this new technology. The few installed systems are at individual level.

The only big nexus system as governmental entity in Mali operates on the Markala's dam on the Niger river. Which is used for irrigation of the rice, it is not an agrivoltaic plant. Due to the lowest electricity access rate in Mali, water and food insecurity in the country and especially the vulnerability of the region to climate change, agrophotovoltaic will be the key technology to provide electricity and water for food processing, irrigation and other activities for rural and decentralized inhabitants over the country.

Chapter 3

3 Materials and Methods

3.1 Introduction

In this section of the study, the data collection method, technical parameters, components, materials and preliminary design of the system to meet the load will be discussed. The study uses secondary data on the integrated business models for decentralized renewable energy solutions from existing studies. Citizens electricity and water demand pour irrigation information was obtained through a field survey across the population and the Malian Company of Textile Development (CMDT). The specification and cost information on the system components were obtained at through question submitted to suppliers. We are going in the hypothesis of the cost €1500/kW.

3.2 Study area

Koutiala is one of the big cities of Mali, a commune, chief town of Sikasso in Mali. The city is located at 140 km north of Sikasso in the north of Mali near the border with Burkina Faso, with coordinates 12° 23′ 22″ N 5° 27′ 50″ W. Its surface area is 18,000 km2 with about 137 919 inhabitants and density about 7.7 habitants/ Km^2 (Environnement et al., 1960). It is the third most populated city in Mali after Bamako and Sikasso. Koutiala has several villages. The city of Koutiala has become the second largest industrial city in Mali after Bamako, mainly thanks to cotton and the CMDT, which have enabled the construction of 4 cotton ginning plants and 2 oil mills. Other units built by the private sector include a soft drink production unit and a dairy. The region's economy is essentially based on agriculture.

According to statistics, with a growth rate of 3%, the population of the city of Koutiala increased from 70,852 habitants in 1998 to 87,139 habitants in 2005, an increase of 23%. From 2005 to 2025, the population will increase from 87,139 to 157,383, an increase of 80.6% (Koutiala, 2005). Most of this population live in rural areas. The region has a health center and institutions.

The climate is Sudano-Sahelian in the north and Sudano-Sahelian in the south, with a dry season and a rainy season. Rainfall varies from 800 to 1100 mm in the southern 2/3 of the circle, and is less than 800 mm in the northern 1/3. The rainy season lasts 6 months from May to October. The number of rainy days per year varies from station to station. It averages 67 days in Koutiala, 56 days in Molobala, and 50 days in M'Pessoba and Zébala.

Although rainfall is relatively good, it is still random, which often pushes farmers to adopt production strategies that can be described as defensive strategies in the sense that they aim to limit the risks. There is electricity demand from households and commercial activities.

Figure 3.1: Koutiala location

Source:(Environnement et al., 1960)

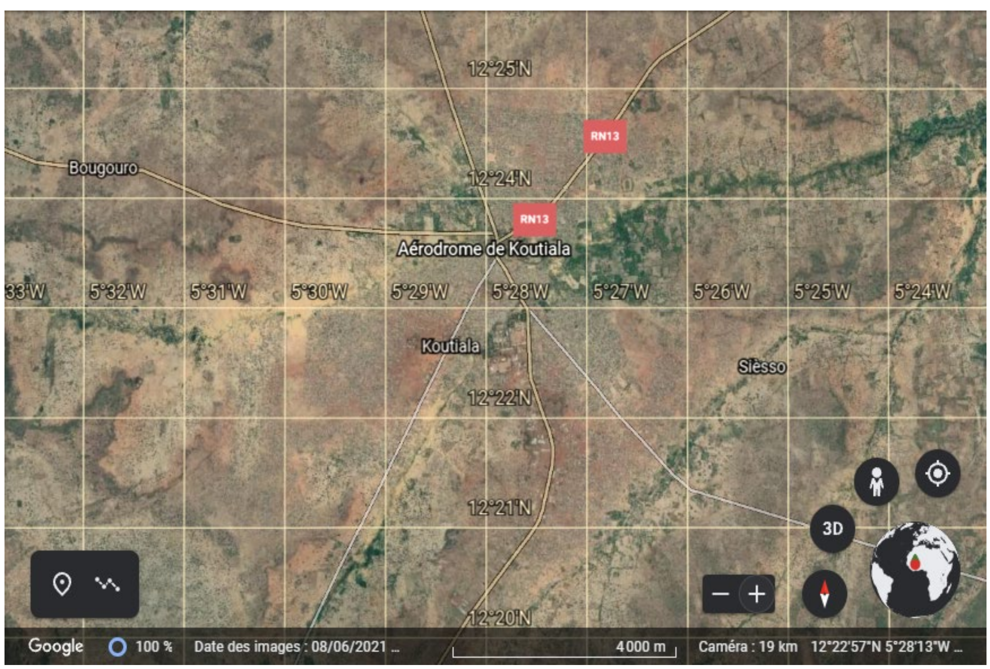


Image from Google Earth

Table 3.1: Key indicators of Koutiala

Region	Koutiala
Coordinates	12° 23’22’ N 5° 27’ 50’ W
Area	18 000 km^2
Population	137,919 inhabitants (2009)
Density	7.7 inhabitants/km^2
Demographic growth rate	5.5%

Source:(Koutiala, 2005)

3.2.1 Koutiala’s energy situation (Koutiala, 2005)

The electricity sector of the city of Koutiala was created in 1972 with the installation of a power station by the EDM. The number of subscribers increased from 310 in 1972 to 1,500 in 2001. Public lighting is represented by about 40 lighting points. But it has known a long period of interruption due to the lack of payment of the bills by the commune.

Despite a large industrial area, Koutiala is handicapped in terms of electricity. Unlike Sikasso and Bougouni, the electricity network in Koutiala does not meet the city's needs. The pumping station with a capacity of 265 m3 /hour and the water tower with a capacity of 1000 m3 are located near the TP subdivision. The network is 58 kilometers long and supplies 52 standpipes and 1,200 1,200 subscribers. The coverage rate of the city's needs is estimated at 70%. Modern and small-scale industries (4 ginning factories, 1 oil mill, traditional soap factories, 3 bakeries, 1 beverage factory, etc.) represent a significant potential demand for electricity.

Energy of Mali (EDM SA) mainly supplies the city of Koutiala with electricity. The total installed power is 1092 KW. The number of subscribers for low voltage electrification is 3112. The number of subscribers for medium voltage electrification is 16. The length of the electrification network is 145.57 km. The length of the expanding network is 20 km. There is an interconnection network for the transport of electricity from Cote d'Ivoire. The supply of the commune of Koutiala is considered by this interconnection project (line Ferkessedougou/Côte d'Ivoire - Sikasso/Mali - Koutiala/Mali - Ségou/Mali). In M'Pessoba, there is an electrification project. The Yelen Kura structure (production of electricity from solar panels) serves the localities of Baramba, Konséguéla, Koutiala, Molobala and M'Pessoba with solar panels. The extension of the rural electricity network through the Yeelen Koura structure, the extension of the Sélingué electricity network, as well as the EDM expansion projects should allow for a more adequate supply of electricity to the region. supply of electricity to the region.

3.2.2 Koutiala's water situation (Koutiala, 2005)

The population increase of about 105% between 1998 and 2025 in the circle, and the circle, and from 122 to 153% in the city of Koutiala, will require the programming and construction of new infrastructure to meet these needs.

Thus, the current water supply deficit is estimated at 2.758 million m3 for the district, and the new needs between 1999 and 2025 to 10.480 million m3. This requires an effort to build 210 wells and boreholes to absorb the deficit in 1999, and 798 new wells and boreholes to meet the new needs between 1999 and 2025, i.e. 30 to 31 wells and boreholes per year on average.

The first step will therefore be to make up the existing deficits by updating them and prioritizing the communes that have been practically forgotten until now, and secondly, to set up and implement a program to strengthen basic infrastructure and taking into account the standards and ratios provided for in the sectoral programs, and the increase in population of 2.7% per year between 1998 and 2025 for the district, and from 3 to 3.5% for the city. 3 to 3.5% for the city of Koutiala.

The water supply facilities are in the form of boreholes, modern wells and standpipes. in the form of boreholes, modern wells and standpipes. There are 15 standpipes in 13 communes: Fagui, Sinkola, Konina, Miéna, Kafo-Faboli, Konséguéla, N'Tossoni, M'Pessoba, Sincina, Nafanga, Zébala, Zafigui and Gouadji-Kao. In 1999, there were a total of 171 boreholes in the rural communes of the circle. The communes with the fewest wells are N'Goutjina, Zafigui and Zanina. The communes with the most wells are M'Pessoba (12 boreholes), Konséguéla (11 boreholes) and Kolonigué (9 boreholes).

The Circle of Koutiala has 57 km long water distribution network and 1030 connections. The water supply system in the city of Koutiala is managed by Energie du Mali (EDM) and is supplied by two boreholes at Sogomougou. The water potential of the Circle is estimated at 7,227,000 cubic meters.

In the city of Koutiala and its hinterland, the number of water infrastructures by type is shown in the table below:

Table 3.2:Number of hydraulic infrastructures by type

Types	Number
Drilling	201
Modern wells	608
Water supply	6
Fountain terminal	15
Pump	423

Source: Hydraulic Koutiala

There are 15 standpipes and 201 boreholes. The spatial distribution of the standpipes does not allow the satisfaction of all the needs in drinking water. There are often several standpipes that are close to each other. As for the wells, their number is estimated at 608.

The supply of drinking water by EDM shows a variable number of new connections depending on the year.

Table 3.3:Evolution of the number of connections from 1991 to 2001

Year	Number
1997	121
1998	98
1999	215
2000	141
2001	103

Source: EDM Koutiala

Few households use standpipes (12.3%) and only 3.9% use boreholes or other developed sources. The vast majority use undeveloped wells (78.5%).

3.2.3 Environmental context of Koutiala (Koutiala, 2005)

Koutiala currently has serious sanitation problems on several fronts:

- The textile industry pollutes the environment of the industrial zone with waste from cotton processing;

- Solid waste produced by the commercial center and by households is neither collected nor evacuated due to a lack of equipment at the municipal road level.

3.3 Methodology

In order to design a agrophotovoltaic, we are going firstly to assess the energy and water need of population of ten villages of Koutiala. After that, RETScreen software is used to determining the annual or monthly global irradiation, temperature of air. PVsyst software was used for sizing the PV components (PV types, regulator and inverter) and define the power to be installed. For this, we are going to choose PV array area about 500 m^2 in PVsyst software directly we get the total installed power. Then across PVsyst database, we can choose our PV panel type with its characteristics (Voltage, current, power and area) to get the total number of panel and inverter that we need for this installation. One part of the energy generated by our system is going to be used to pumping water for agriculture, the remaining will be injected to the grid. The design of agrophotovoltaic system must be optimal in order to supply electricity reliably and economically. The configuration of the components in the agrophotovoltaic system is optimized in order to minimize the LCOE.

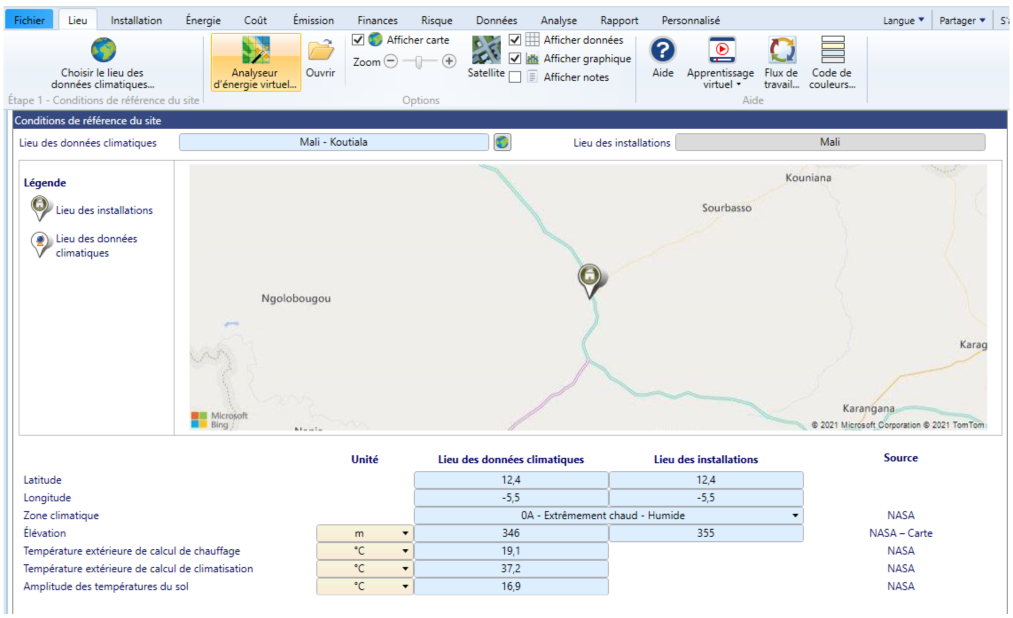
The last part will be the economic analysis using an Excel file. This analysis with an Excel file will evaluate many aspects regarding the profitability of the agrophotovoltaic system, the net present value, the levelized cost of electricity produced, annual revenue, internal return rate and the discounted payback period. Through this analysis, we will also see the effect of some parameters on the LCOE, payback period and annual revenue like government Subsidy, electricity price escalation. Two types of business models are going to be analyzed. The first model was with electricity price €0.10/kWh in year 1 with an escalation of 2%., the second model was with a fixe electricity price over the lifetime (€0.15/kWh). The Excel analysis requires information on the power, annual energy, economic parameters, and the different costs.

3.3.1 Meteorological Data of Koutiala

Meteorological data of Koutiala are loaded online from the NASA database online using the RETScreen software. This technique allows to load climate data online in real time. In our case, we will record the annual horizontal irradiation, the average temperature, the humidity of the region. The steps are shown in the figures 3.2 below. The RETScreen interface is presented as follows:

We are going to launch a new project where we must choose our site and select new site if the site is not in the database (Koutiala). Enter the name of the site (Koutiala), the country (Mali), the region (Africa) and the geographical coordinates will be displayed. Then we select the source of our data (NASA) and click on import.

Figure 3.2: Steps of generation of meteorological parameters of Koutiala



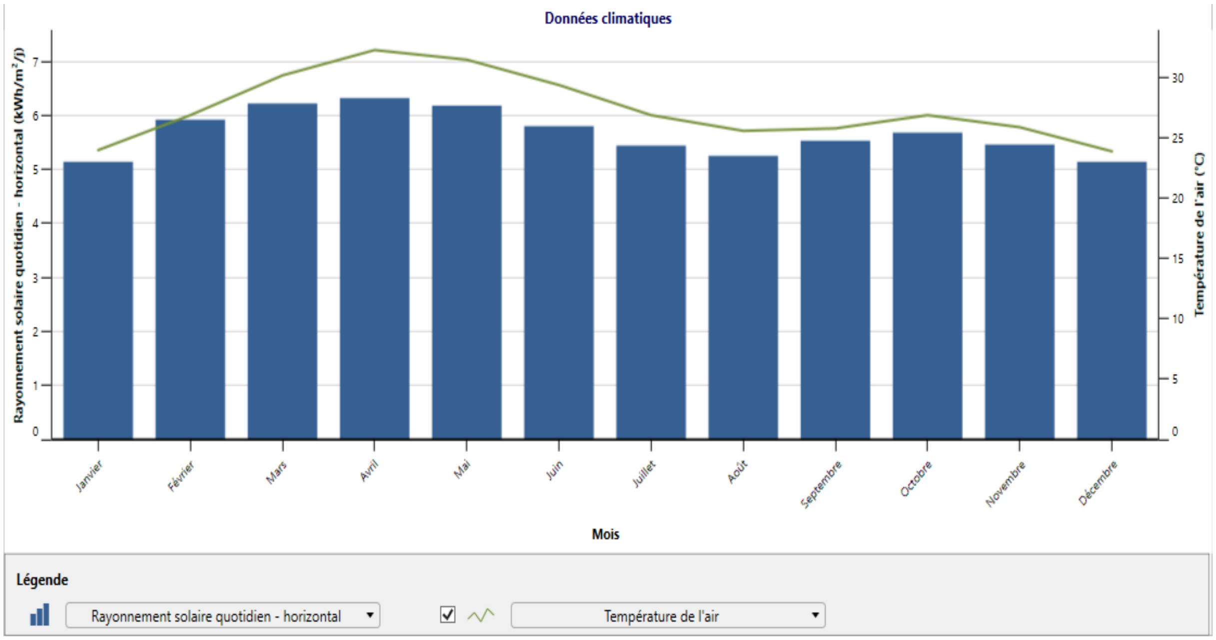
The geological parameters are shown in the figure below:

Figure 3.3: The geological parameters of Koutiala

Mois	Température de l'air	Humidité relative	Précipitation	Rayonnement solaire quotidien - horizontal	Pression atmosphérique	Vitesse du vent	Température du sol	Degrés-jours de chauffage 18 °C	Degrés-jours de climatisation 10 °C
	°C	%	mm	kWh/m²/j	kPa	m/s	°C	°C-j	°C-j
Janvier	24,0	20,8%	0,62	5,14	97,2	4,3	24,9	0	434
Février	26,9	16,1%	1,40	5,92	97,1	4,4	28,1	0	473
Mars	30,2	20,1%	6,20	6,22	97,0	3,8	31,7	0	626
Avril	32,3	32,8%	27,90	6,32	96,9	3,2	34,3	0	669
Mai	31,5	47,6%	68,51	6,18	97,0	3,3	33,2	0	667
Juin	29,4	59,0%	115,80	5,80	97,2	3,2	30,6	0	582
Juillet	26,9	72,3%	186,62	5,44	97,2	2,8	27,5	0	524
Août	25,6	80,9%	241,80	5,25	97,2	2,5	25,8	0	484
Septembre	25,8	79,6%	153,30	5,53	97,2	2,3	25,9	0	474
Octobre	26,9	67,3%	49,91	5,68	97,2	2,3	27,2	0	524
Novembre	25,9	41,7%	3,60	5,46	97,1	3,1	26,0	0	477
Décembre	23,9	27,6%	0,31	5,14	97,2	4,0	24,3	0	431
Annuel	**27,4**	**47,3%**	**855,97**	**5,67**	**97,1**	**3,3**	**28,3**	**0**	**6 364**
Source	NASA	NASA	NASA	NASA	NASA	NASA	NASA	NASA	NASA
Mesuré à					m	10	0		

And we can also see the evolution of the global irradiation and the temperature during the year.

Figure 3.4: Global irradiation evolution in the year



The different results are resumed in the table 3.4 below:

Site: Koutiala

Country: Mali

Region: Africa

Source: NASA-SSE satellite data 1983-2005

Latitude: 12°23’22°

Longitude: 5°27’50’

Altitude: 356 m

Time Zone: GMT

Albedo: 0.20

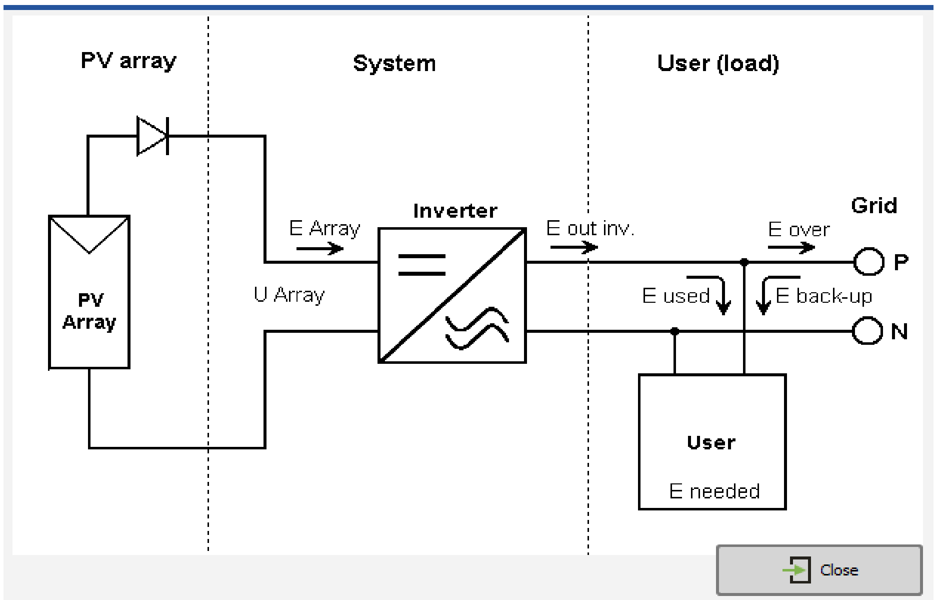
Table 3.4: Meteorological indicators of Koutiala

Month	Global Horizontal irradiation (kW/m^2)	Relative humidity (%)	Atmospheric pressure (kPa)	Air Temperature (°C)	Soil temperature (°C)	Wind speed (m/s
January	5.14	20.8	97.2	24.0	24.9	4.3
February	5.92	16.1	97.1	26.9	28.1	4.4
March	6.22	20.1	97.0	30.2	31.7	3.8
April	6.32	32.8	96.9	32.3	34.3	3.2
May	6.18	47.6	97.0	31.5	33.2	3.3
June	5.00	59.0	97.2	29.4	30.6	3.2
July	5.44	72.3	97.2	26.9	27.5	2.8
August	5.23	80.9	97.2	25.6	25.8	2.5
September	5.53	79.6	97.2	25.8	25.9	2.3
October	5.68	67.3	97.2	26.9	27.2	2.3
November	5.46	41.7	97.1	25.9	26.0	3.1
December	5.14	27.6	97.2	23.9	24.3	4.0
Annual	5.67	47.3	97.1	27.4	28.3	3.3

3.3.2 Photovoltaic generator configuration

The typically configuration of the different components of the agrivoltaic system is shown as follow:

Figure 3.5: Typical configuration of the agrivoltaic system



Source: PVsyst software

3.3.2.1 Photovoltaic array

PV array is constituted by 300 panels of types Si-mono Aleo Solar with unit power of 305 Wc/26 Voltage, connected 20x15 (20 strings of 15 series) with a lifetime of 25 years and a mounting structure of 2.5 m. The energy produced by the system is about 156 MWh / year. The detailed specifications and the I-V characteristics of the module at different insulations and temperatures are shown in table 3.5 (PVsystem database). The cost of solar PV modules is dependent on factors such as the size of panel, type of technology (mono or polycrystalline), the brand manufacturer, the retailer and country in particular.

Table 3.5: Technical specification of Aleo Solar SI-mono 305 Wc/26V panel

Parameters	Specification
Technology	Si-mono
Dimensions	1660mm x 990mm x 50.0mm
Cell Arrangement:	1x 60
Weight	20.00 Kg
Nominal Power (STC)	305 Watts
Maximum Power (Pmax):	307.7 Watts

Optimum Operating Voltage Vmp:	31.4 Volts
Optimum Operating Current (Imp):	9.7 Amps
Open Circuit Voltage (Voc) :	39.5 Volts
Short Circuit Current (Isc) :	10.06 Amps
Module Efficiency:	18.72%
Operating Temperature	-40°C to 70°C

3.3.2.2 Solar Inverter

Since solar PV arrays provide DC output, a power converter system is required to convert DC output from the PV to AC to be used in the system. A power converter maintains the flow of energy between the AC electrical load (Grid). Costs of inverters vary based on their sizes. For this study, Multi MPPT 7.5 kWac model of inverter with 2 MPPT input is selected. The lifetime assumed for the converter is 10 years. The technical specifications of this inverter are shown in the table 3.6

Table 3.6: Technical specifications for converter/inverter

Parameters	Specification
Rated Power	7.5 Kva / 8 Kva
Max. AC power at 25°C	8 kVA
Nominal MPP Voltage	450 Volts
Minimum MPP Voltage	150 Volts
Maximum MPP voltage	750 Volts
Absolute max PV voltage	900 Volts
Frequency	50 Hz/60Hz
Nominal PV Power	8 Kw
Maximum PV Power	10 Kw
Maximum PV current	38 Amps
Grid Voltage	230 Volts
Nominal AC Power	7.5 Kva
Maximum AC Power	8 Kva
Nominal AC current	18 Amps

Maximum AC current	20 Amps
Maximum efficiency	98.5%

3.3.2.3 Load

In this study, the electricity produced is shared in two parts, firstly to supply a water pumping system for agriculture, the remaining power is injected to the grid.

3.3.2.4 Technical and economic parameters

The technical and economical parameters of the system are resumed in the table 3.7. A capital investment concerns the agrivoltaic technologies installed at Koutiala, Mali: solar panel array, consisting of 300 units of 305 Wp, configured in 20 parallel strings of 15 modules (20 x 15), with an installed capacity of 92.7 Kw; solar inverter, consisting of 10 units with 2 MPPT inputs of 7.5 Kva; solar water pump of (… MWh). The total investment costs for the system are €140,000. These products are procured with 0% government subsidy. Inverters for this system are to be replaced in Year 10 at a cost of €8000. Electricity generated in Year 1 from the system are 156,680.00 kWh, and each of these production levels is expected to degrade by 1% each year. The real average discount rate of 5%. Operation and maintenance costs (O&M) is assumed to be 0.5% of Investment Cost, while Electricity price in Year 1 is taken as €0.10/kWh. Due to possible changes in electricity tariff, an escalation rate of 2% per annum was assumed appropriate from Year 2 to 25.

Table 3.7: Summary of Technical and financial input data required for designing and analysing

Technical and economic data	
Electricity Generation	156 MWh/ year
Real interest rate	5%
Lifetime	25 years
Electricity Generation Degradation rate	1%
CAPEX	€140,000
Government Subsidy	0%
Cash Equivalent of Government Subsidy	€0
Installed Cost	€140,000

Specific Installed cost	€1500/Kw
Inverter replacement Cost	€8000
Annual O&M Cost as percentage of CAPEX	0.5%
Electricity price in year 1	€0.10/kWh
Electricity Price Escalation Rate	2%

The food crops that were assumed to cultivate under the PV field in this case are: tomato, carrot, okra and salad.

3.4 Definition of some keys indicators

- NPV is the net present value; equivalent value of one or more cash flows at a reference point in time called the present. NPV is an indicator of how much value an investment or project adds to the firm. It determines if the project can be accepted or rejected. It can be find using the excel function **P= NPV (rate, range).**
- The levelized cost of energy (LCOE), or levelized cost of electricity, is a measure of the average net present cost of electricity generation for a generating plant over its lifetime.
- Discounted Payback Period determines in how many years it takes to recover the investment (I), taking into consideration the time value of money. For which the following relationship holds

$$\sum_{k=1}^{\theta'}(R_k - E_k)(P/F, i\%, k) - I \geq 0 \quad \textbf{(1)}$$

- The internal return rate (IRR) is the interest rate that equates the equivalent worth of an alternative's cash inflows (revenue, R) to the equivalent worth of cash outflows (expenses, E). Hence it is the interest rate at which the discounted present worth of benefits equals the discounted present worth of costs. Mathematically, the IRR is the interest i'% at which.

$$\sum_{k=0}^{N} R_k(P/F, i'\%, k) = \sum_{k=0}^{N} E_k(P/F, i'\%, k) \qquad \textbf{(2)}$$

Or by the excel function **i'= IRR(range,[guess])**

Chapter 4

4 Results and Discussions

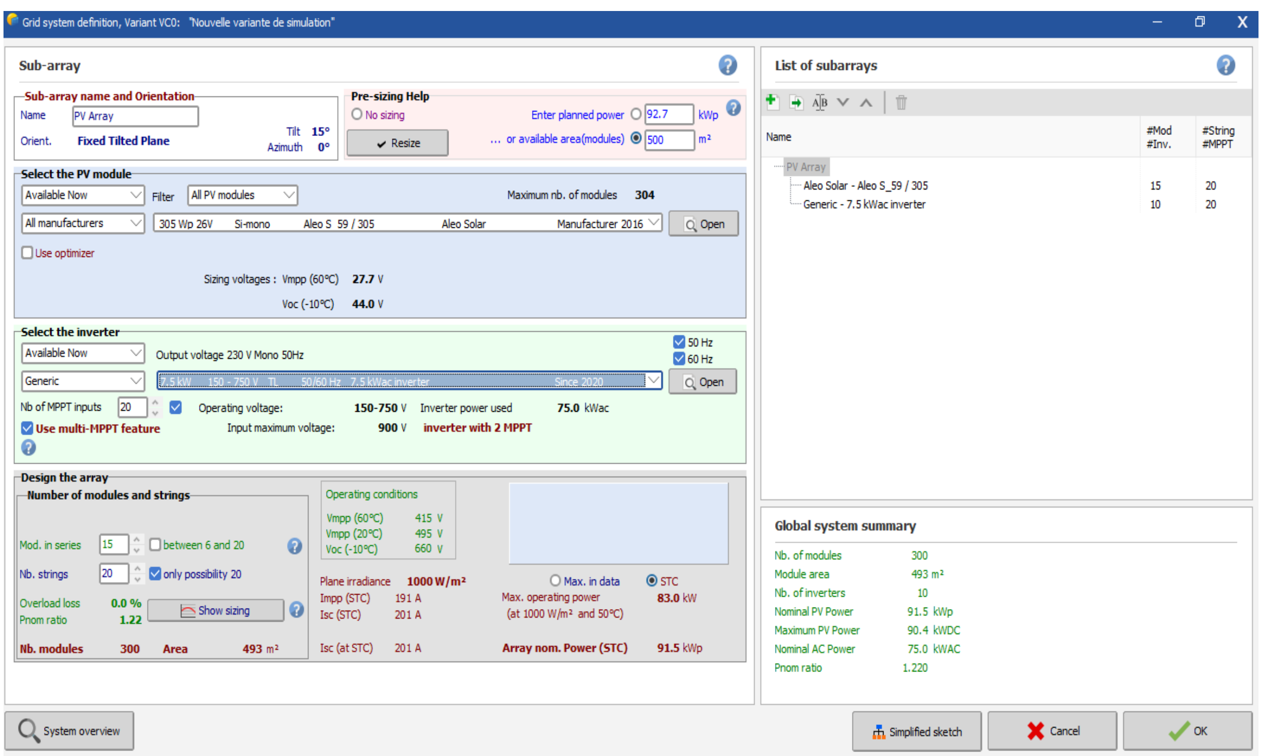
4.1 Introduction

This chapter presents the summary of the technical simulations performed using Excel file for the study area. The economic analysis in the part concerned only the electricity sold to the grid.

4.2 The load definition

Our load is defined as follow, firstly are expected to irrigate one hectare of market gardening. The amount of daily water need is expected to be 60 $m^3/ha/day$ and the power need to provide this flow is 12 kWp. As we want sell electricity to grid after irrigation, we are going to install 500 square meters of solar panel areas. From PVsyst these 500 square meters give us a power of 92.7 kWp and an energy of 156680 kwh/year. In this power, 12 kWp will be reserved to drive a solar pump to irrigate the one hectare, the remaining power will be injected to the electrical network. The cost of the system is estimed as €1500/KW that gives us €140000 as Capex.

Figure 4.1: The load definition with PVsyst



4.3 Program presentation

This Excel file is the one we saw during the energy economic and finance course with Dr. Emmanuel A. Donkor. In this file, we have to input the different data and derived variables.

Figure 4.2:Excel file

				EOY	Year	CAPEX	Gov Sub	Inverter	Elec. Generation	Electricity Price	O&M	Revenue	Net Cash Fl
2							Alternativ Agrivoltaic System						
3	**Data**	grivoltaic Economic analyse		EOY	Year	CAPEX	Gov Sub	Inverter	Elec. Generatior	lectricity Price	O&M	Revenue	Net Cash Fl
4	Real Discount Rate (i), %	5,0%		0	2022	(140000,0)	0,00						(140000,
5	Study period (N), yrs	25		1	2023				150 000,0	0,1000	(700,00)	15 000,0	14300,
6	Installed capacity, kW	92,7		2	2024				148 500,0	0,102	(700,00)	15 147,0	14447,
7	Inverter Useful Life (M), yrs	10		3	2025				147 015,0	0,104	(700,00)	15 295,4	14595,
8	**Data/Derived Variables**			4	2026				145 544,9	0,106	(700,00)	15 445,3	14745,
9	Electricity Generation, kWh	150000		5	2027				144 089,4	0,108	(700,00)	15 596,7	14896,
10	Electricity Generation Degradation rate, %	1,0%		6	2028				142 648,5	0,110	(700,00)	15 749,5	15049,
11	CAPEX, €	140 000,00		7	2029				141 222,0	0,113	(700,00)	15 903,9	15203,
12	Government Subsidy, %	0,0%	<--Decision	8	2030				139 809,8	0,115	(700,00)	16 059,8	15359,
13	Cash Equivalent of Government Subsidy, €	0		9	2031				138 411,7	0,117	(700,00)	16 217,1	15517,
14	Installed Cost, €	140 000,00		10	2032			(8000,00)	137 027,6	0,120	(700,00)	16 376,1	7676,
15	Specific Installed cost, €/kW	1510,25		11	2033				135 657,3	0,122	(700,00)	16 536,6	15836,
16	Inverter replacement Cost, €	8 000,00		12	2034				134 300,7	0,124	(700,00)	16 698,6	15998,
17	Annual O&M Cost as percentage of CAPEX, %	0,5%		13	2035				132 957,7	0,127	(700,00)	16 862,3	16162,
18	Annual O&M, €	700,00		14	2036				131 628,2	0,129	(700,00)	17 027,5	16327,
19	Electricity price in Yr 1, €/kWh	0,1000	<--Decision	15	2037				130 311,9	0,132	(700,00)	17 194,4	16494,
20	Electricity Price Escalation Rate, %	2,0%		16	2038				129 008,8	0,135	(700,00)	17 362,9	16662,
21	**Finacial Indicators**			17	2039				127 718,7	0,137	(700,00)	17 533,0	16833,
22	**PV Cost**	(164741,045)		18	2040				126 441,5	0,140	(700,00)	17 704,9	17004,
23	**PV Prod**	€ 1 925 767,99		19	2041				125 177,1	0,143	(700,00)	17 878,4	17178,
24	**LCOE**	(0,09)		20	2042			(8000,00)	123 925,3	0,146	(700,00)	18 053,6	9353,
25	**NPV**	€ 74 731,93		21	2043				122 686,0	0,149	(700,00)	18 230,5	17530,
26	**AW**	€ 5 302,41		22	2044				121 459,2	0,152	(700,00)	18 409,2	17709,
27	**IRR**	10%		23	2045				120 244,6	0,155	(700,00)	18 589,6	17889,
28	**PV revenue**	€ 232 524,11		24	2046				119 042,1	0,158	(700,00)	18 771,7	18071,
29	**Pay back period**	17,712		25	2047				117 851,7	0,161	(700,00)	18 955,7	18255,

4.4 Economic analysis of the first scenario (€0.10/kWh with escalation of 2%)

Table 4.1: Result of the base case analysis of the first scenario

Financial indicators	Value
CAPEX	€140,000
NPV	€74,732
LCOE	€0.09
IRR	10%
AW	€5,302
Payback Period	18 year

The simple analysis in the business model 1 of the agrivoltaic system gives us the following results. The present net value of the system is €74,732 positive, which means that the inflow of revenue is higher than the outflow of expenses, economically the system is profitable therefore viable and the project can be retained. Other financial indicators can support this profitability. The Annual Worth (AW) equals €5,302 also positive and the IRR equals to 10% higher than MARR 5%, these two indicators confirm the previous conclusion. The Levelized cost of electricity LCOE equals €0.09/kWh which is reasonable if we look at the electricity cost (€0.10/kWh) with escalation of 2%. The project will start to make profit in the 18th year after the system is put into operation. The simple analysis in the business model 1 of the agrivoltaic shows us satisfactory results on the profitability of the system. The electricity production degrades over the lifetime of the plant due to the age of the components.

4.5 Sensibility analysis

This analysis is to see our business is sensible in which parameter.

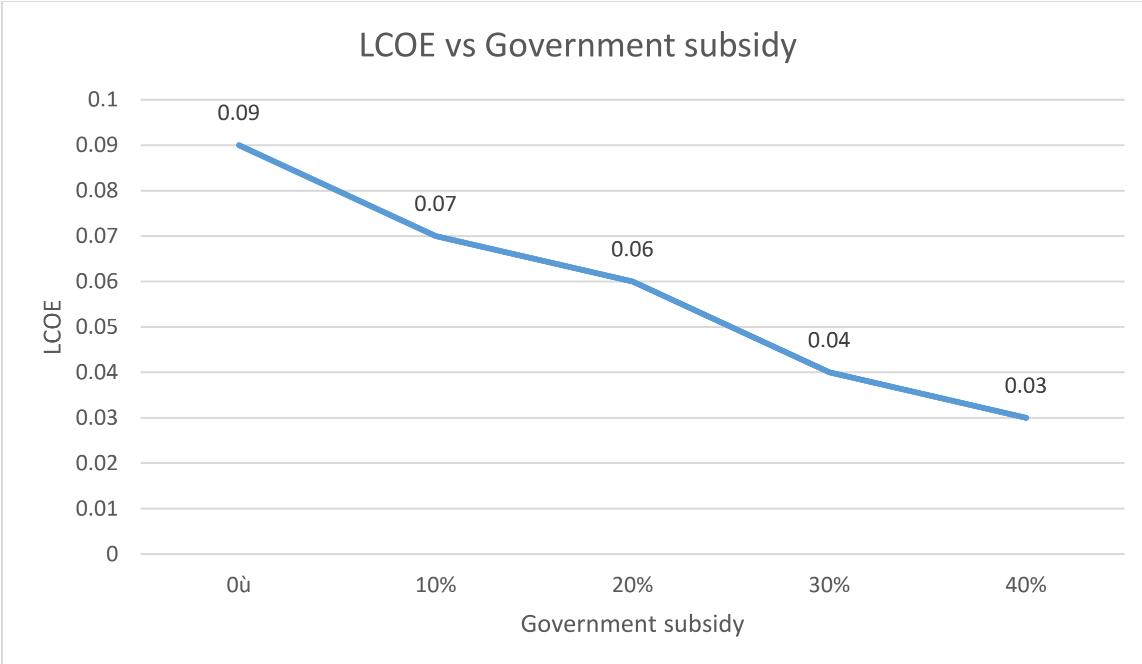
4.5.1 Scenario 1: Business model with a variable electricity price over lifetime

4.5.1.1 Government subsidy effect on the project profitability

Table 4.2:Effect of Government subsidy on financial indicators

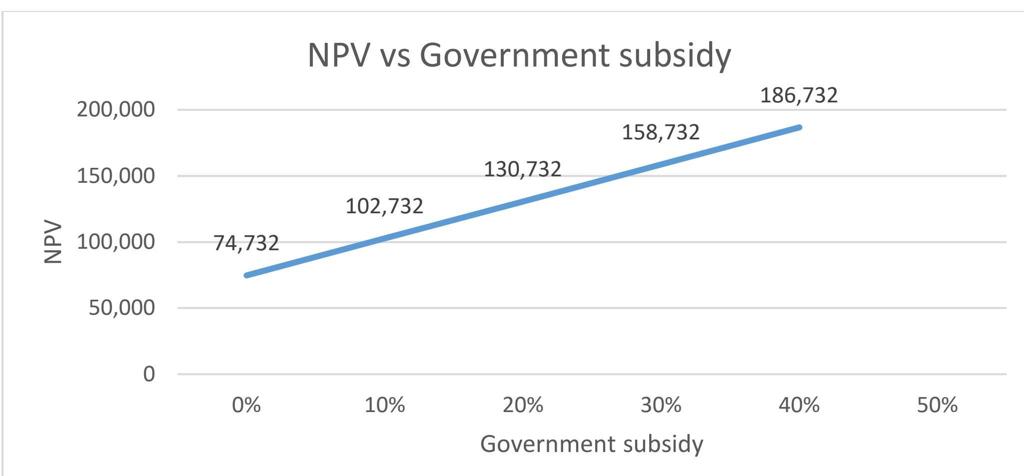
Government subsidy	0%	10%	20%	30%	40%
CAPEX	€140,000	€126,000	€112,000	€98,000	€84,000
NPV	€74,732	€102,732	€130,732	€158,732	€186,732
LCOE	€0.09	€0.07	€0.06	€0.04	€0.03
IRR	10%	13%	17%	26%	52%
Payback Period	18 years	15 years	12 years	9 years	7 years

Figure 4.3: Evolution of LCOE with government subsidy



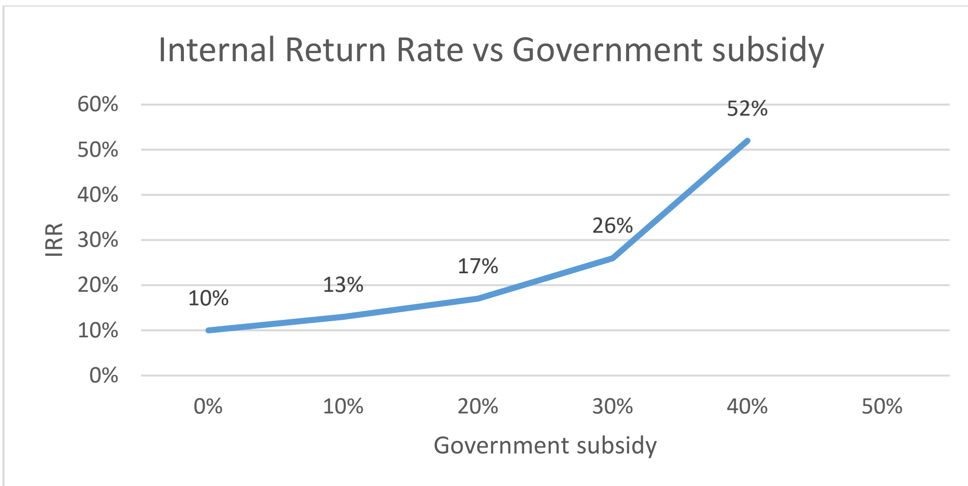
In this graph, we see clearly the effect of the government subsidy on the levelized cost of electricity in this case. LCOE decreases significantly if the government subsidy increases. The value become zero for the higher government subsidy. That means that the subsidy for this type of project is very benefit for the cost of electricity production. And it can motivate the investor to investigate in the sector.

Figure 4.4: Evolution of NPV with government subsidy



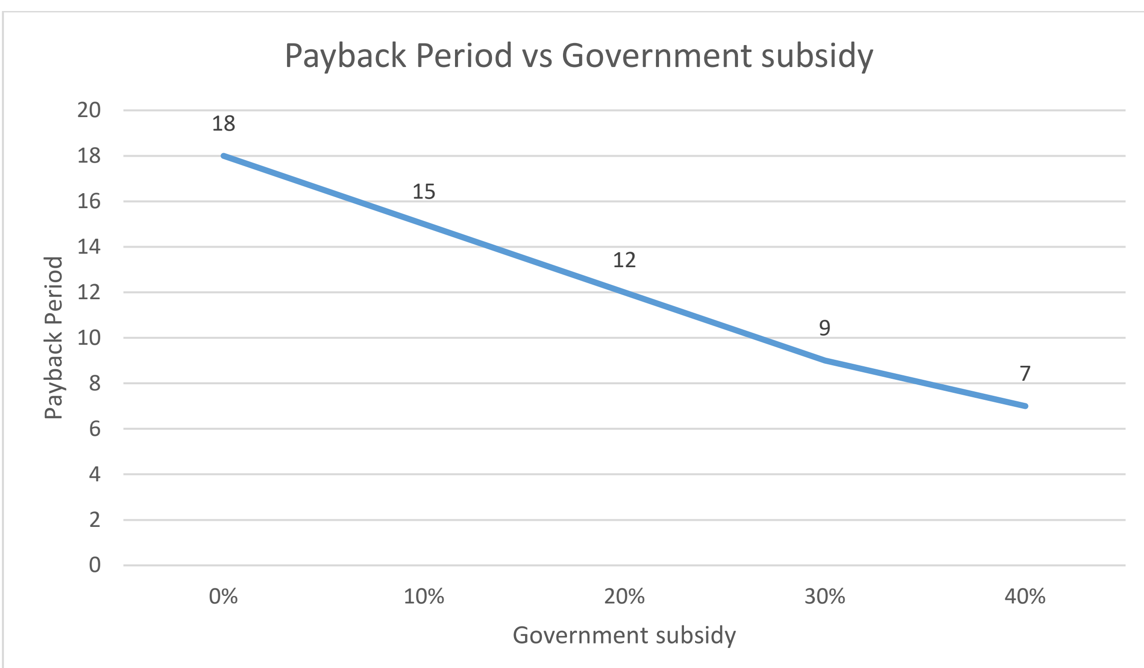
The effect of government subsidy the net present value of our project is highly considerable. NPV go from €74 732 to €186 732 which corresponds to a rate of 40%. The government subsidy can make a non-profitable project (NPV negative) a profitable project (NPV positive) for an investor.

Figure 4.5: Evolution of IRR with government subsidy



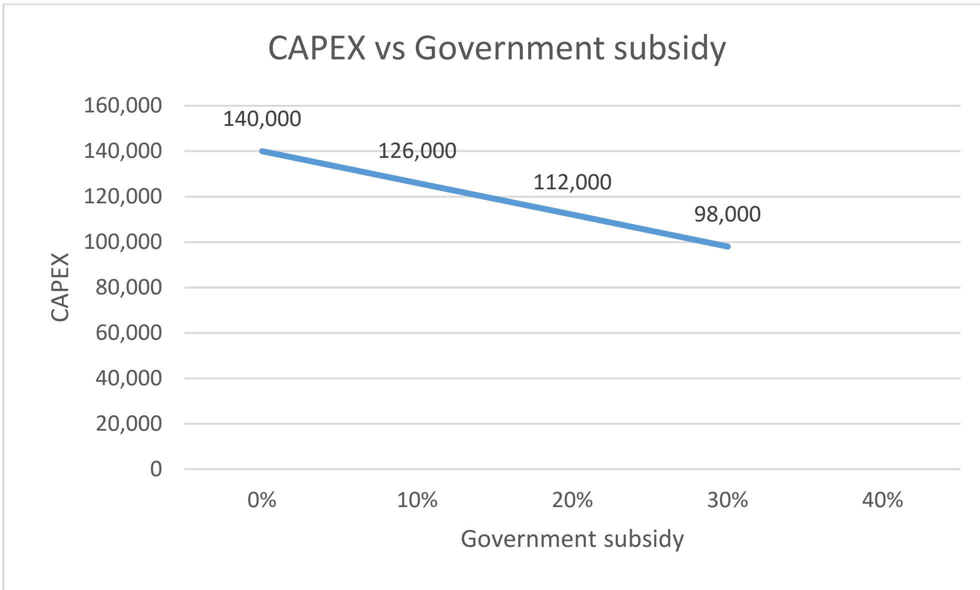
The internal return rate (IRR) of our project increases with the government subsidy.

Figure 4.6: Evolution of the Payback Period with government subsidy



Our business project should take 18 years before making profit but with the government subsidy, this period decreases. That means that if the project should take 18 years before making profit with government subsidy it will take less.

Figure 4.7: Evolution of CAPEX with government subsidy



In summary, it is clear that this scenario 1 of our business project is sensitive to government subsidy. The higher the government subsidy, the higher the profitability. This allows us to conclude that a government subsidy is very important to support the agrivoltaic system investment in Koutiala where most of the solar components are imported. The subsidy influences all financial indicators and the investment cost. There is a decrease in the Capex and the payback period, however, the net present value with the government subsidy rate. The public support is the best way to promote agrivoltaic system for agriculture and irrigation, to improve the water accessibility for food processing.

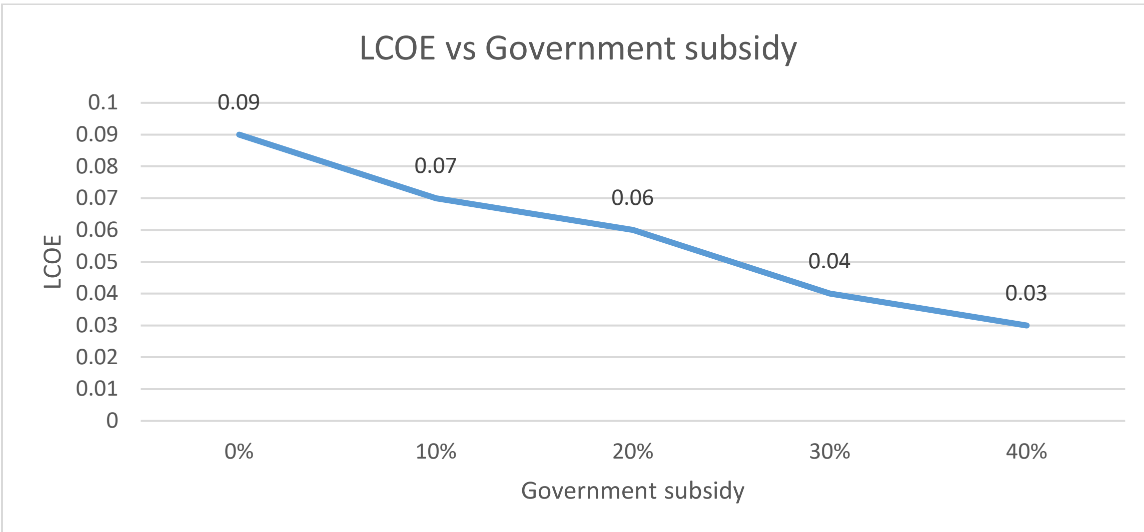
4.5.2 Scenario 2: Business model with fixe electricity price €0.15/kWh

Table 4.3: Effect of Government subsidy on financial indicators

Government subsidy	0%	10%	20%	30%	40%
CAPEX	€140,000	€126,000	€112,000	€98,000	€84,000
NPV	€131,073	€159,073	€187,073	€215,073	€243,073

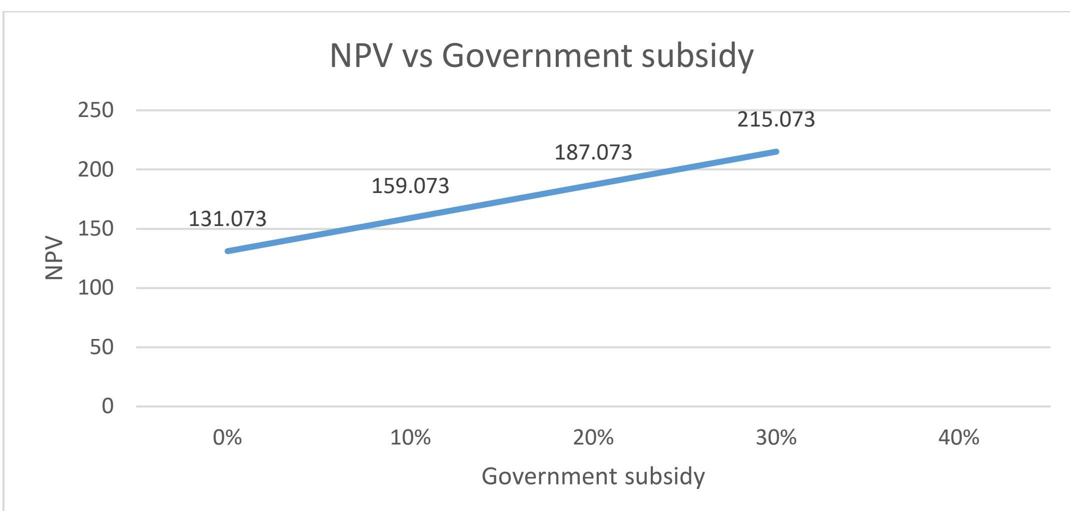
LCOE	€0.09	€0.07	€0.06	€0.04	€0.03
IRR	14%	18%	25%	38%	77 %
Payback Period	14 years	12 years	9 years	7 years	5 years

Figure 4.8: Evolution of LCOE with government subsidy scenario 2



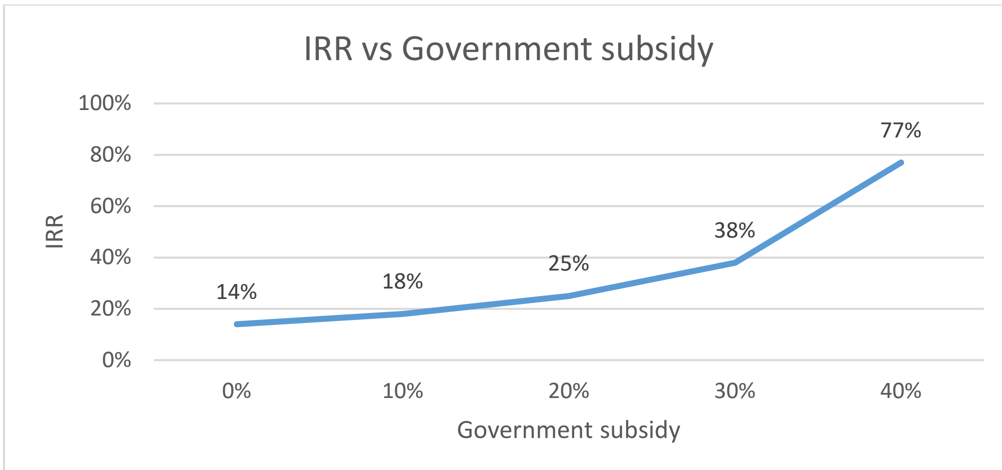
Here, we see that the effect of the government subsidy on the levelized cost of electricity is the same in the different cases. LCOE decreases significantly if the government subsidy increases. Levelized cost of electricity production is the same. Therefore, we can't choose the scenario with the high profitability basing on LCOE.

Figure 4.9: Evolution of NPV with government subsidy



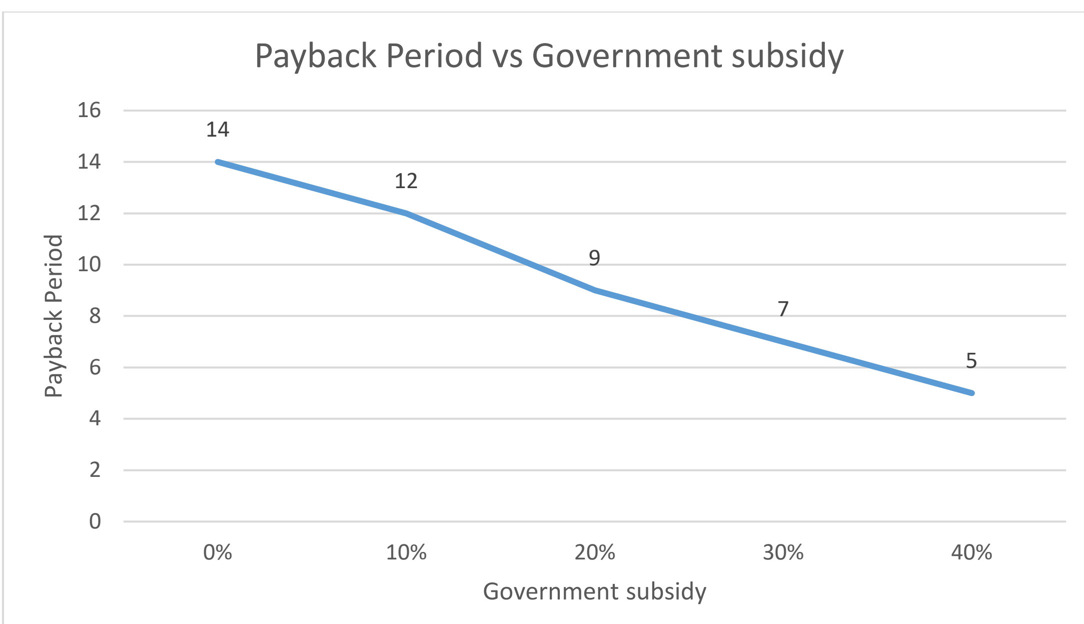
Look at the net present value of the two scenario to see the most profitable project in our case. The NPV of this business model is very higher than the first business model, that means the difference between inflow and outflow is considerable. Therefore, this business model is economically very profitable in term of net present value.

Figure 4.10: Evolution of IRR with government subsidy



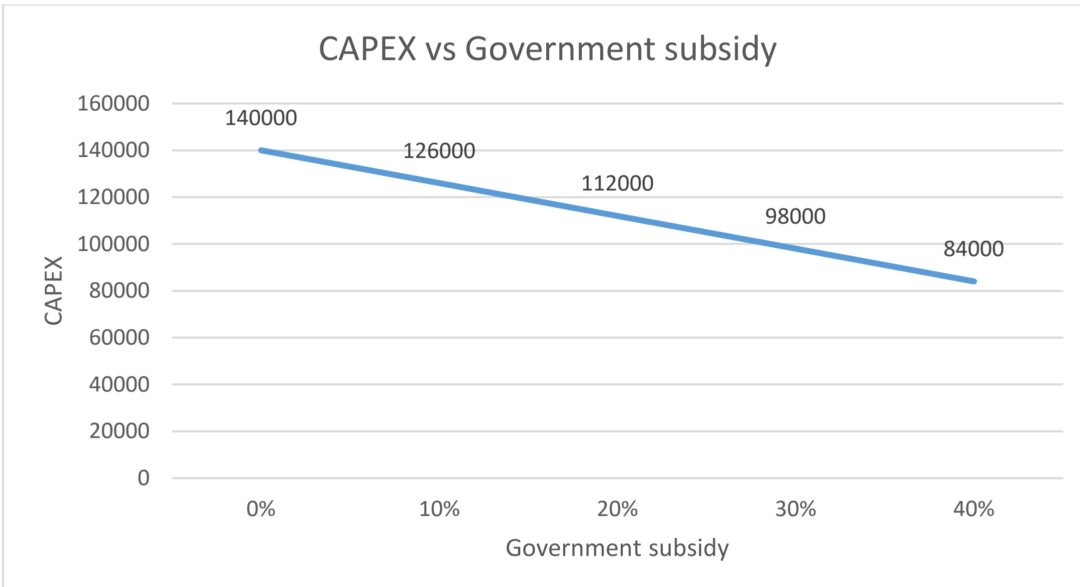
The IRR of this model increases with government subsidy and it is very important than the first business model, therefore, this model is given much profit than the first.

Figure 4.11: Evolution of the Payback Period with government subsidy



This business model should only take 14 years before making profit instead 18 years in the first case, but with the government subsidy, this period decreases. The Payback Period of this business model is less than the Payback Period in the first model. Therefore, this model is better than the first one.

Figure 4.12: Evolution of CAPEX with government subsidy



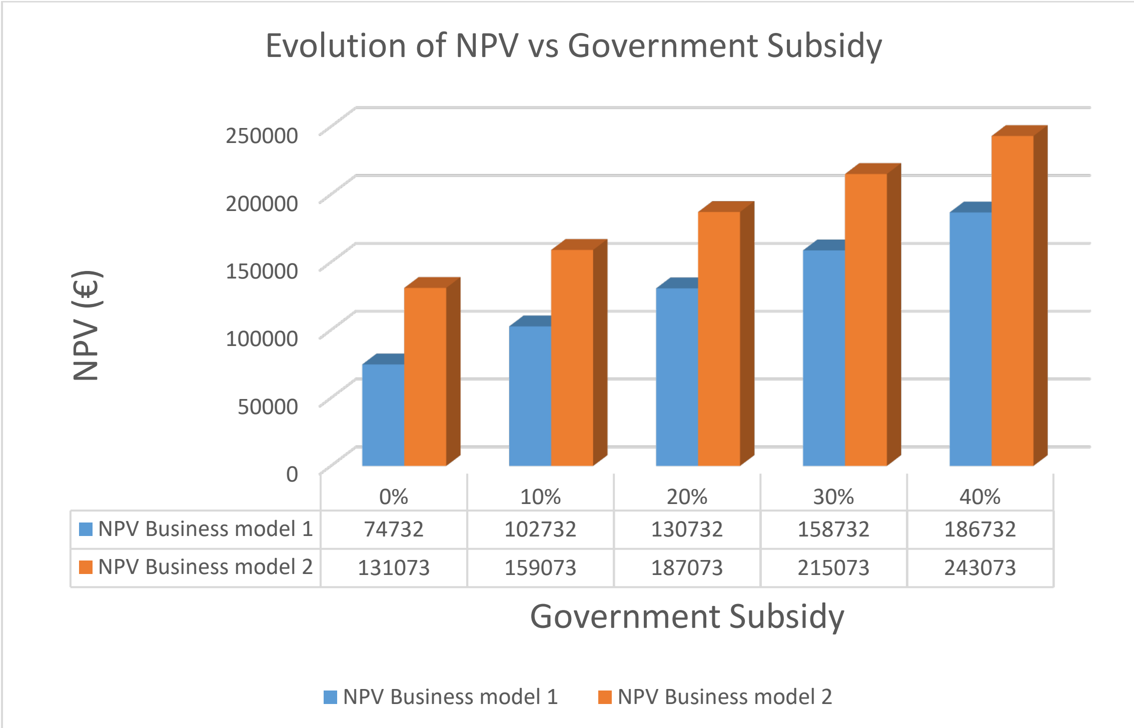
The CAPEX is the same in both business model.

After the sensitive analysis of these two business models, we are going to use the business model 2 because it gives us the high net present value (NPV), the less levelized cost of electricity (LCOE), the high internal return rate (IRR) and it gives us profit in less time than the first model.

4.6 Comparison between the two business models

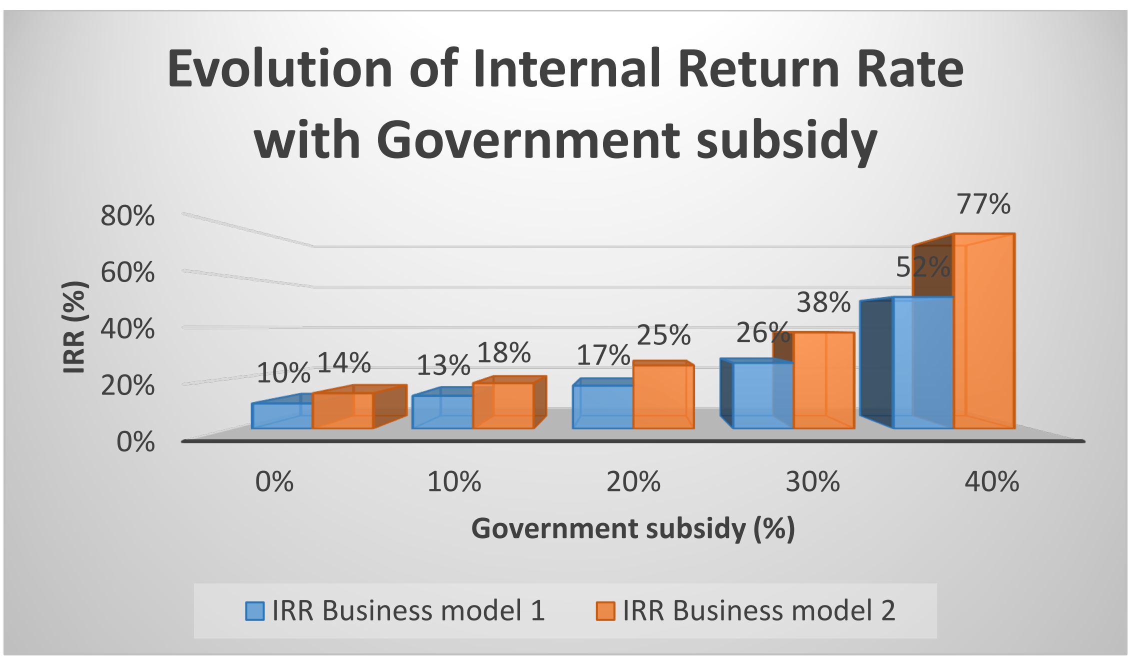
4.6.1 NPV comparison

In the figure below, we can clearly see that the NPV of the business model1 is less than the NPV of the business model 2 at the same government subsidies. Therefore, if we are going to choice a business regarding the NPV, our choice will be the business model with the higher NPV so the business model 2.



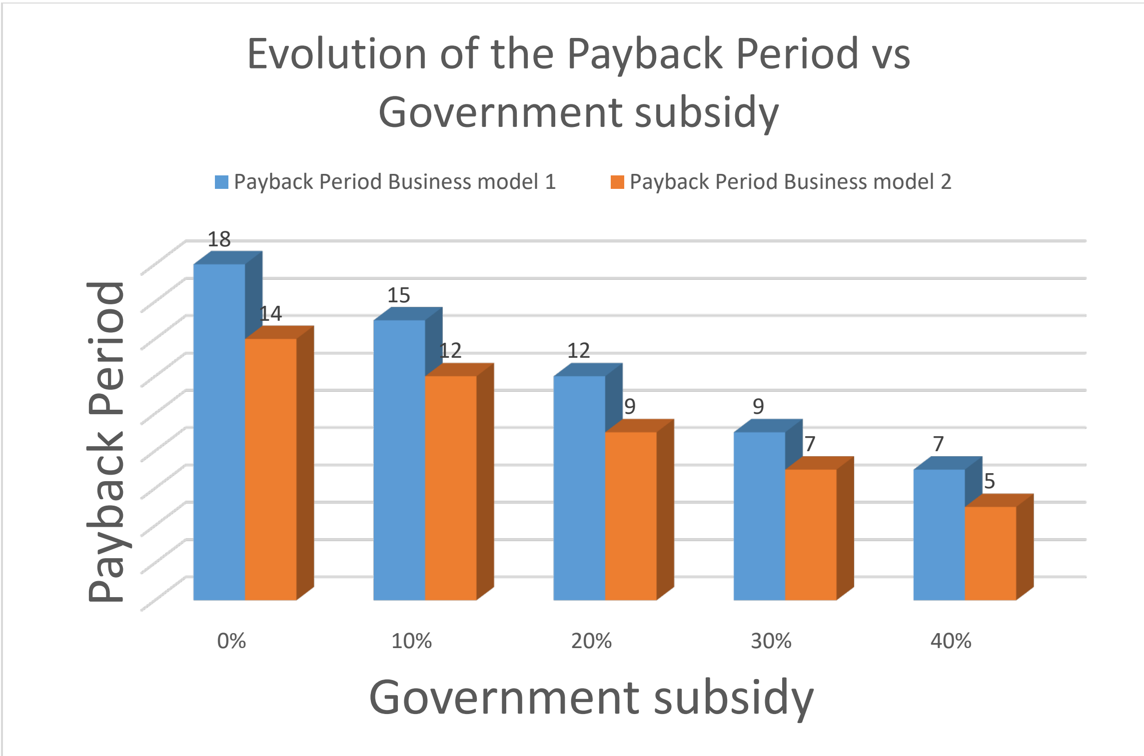
	0%	10%	20%	30%	40%
NPV Business model 1	74732	102732	130732	158732	186732
NPV Business model 2	131073	159073	187073	215073	243073

4.6.2 Internal Return Rate (IRR) comparison



It is show in this graph that the IRR of the business model 2 is higher than the IRR of the business model 1 at the same government subsidy. This means that the business model 2 is more profitable than the first one.

4.6.3 Discounted Payback Period comparison



The investment recover period in the business model 2 is less than in the business model 1 without government subsidy. They decrease in this sense with the different values of government subsidies.

Chapter 5

5 Conclusion and Recommendation

5.1 Conclusion

The aim of this study was to integrate energy-water-food into the business model for a decentralized renewable energy solution. The combination of energy and water plays a considerable role in food security and sustainable development in the world especially in Sub-Saharan Africa. Agrivotaic system, which is not widely used in Africa, is a better solution to provide reliable, affordable and clean electricity, clean water and to enable sustainable food security for people living in rural and remote areas. The development of agrivoltaic systems in Africa is essential to achieve the United Nations Sustainable Development Goals agenda 2030 especially Goals 2, 7 and 13. The investment in agrivoltaic in Koutiala for electricity production, water pumping and wastewater treatment, and irrigation presents enormous benefits. There are enormous resources in energy, water and cultivable land, a good policy of management and investment in these resources allow to answer the various stakes related to electricity, water, and to participate in the economic development of the region. The system allows in a first time a clean, reliable and affordable electricity production; water pumping and treatment, and finally agriculture and irrigation. Environmental data such as ambient temperature, relative humidity, global irradiation, etc. were obtained from NASA Surface Meteorology Database online. The system composed of 92.7 kW of solar PV array, 75kW of inverter is designed with PVsyst software. The economic analysis of the two types of business models allows us to identify the most profitable business model to adopt in the region. The different analyses give us the following results: the same LCOE equal €0.09, Present net Value (NPV, case2) €131,073 higher than the net present value (NPV, case 1) €74,732, Internal Return Rate IRR (case 2) 14% is higher than IRR (case 1) 10%, the Payback Period (case 1) 18 years is higher than the Payback Period (case 2) 14 years. All of these financial indicators are shown that the business model 2 is economically more profitable therefore viable. We can invest in the second business models and after 14 years, we will start to make profit. This model will provide a reliable, affordable and clean electricity; clean and fresh water for irrigation to improve food security without negative effect on the environment.

5.2 Recommendation

- This study can be simulated with meteorological data from any other region of Mali.
- To complete this economic analysis, the future study should add income from food-crops.

- The future study should be done with an energy storage system (Batteries) to see which one is profitable economically
- The government should promote and subsidize solar energy
- The government should put in place a plan for the management and development of renewable energy integrated with agriculture.
- Explaining to the farmers that they can work all the year not only in the rain season.

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7 APPENDIX

APPENDIX I

Figure I-a: Koutiala map (Google Earth)

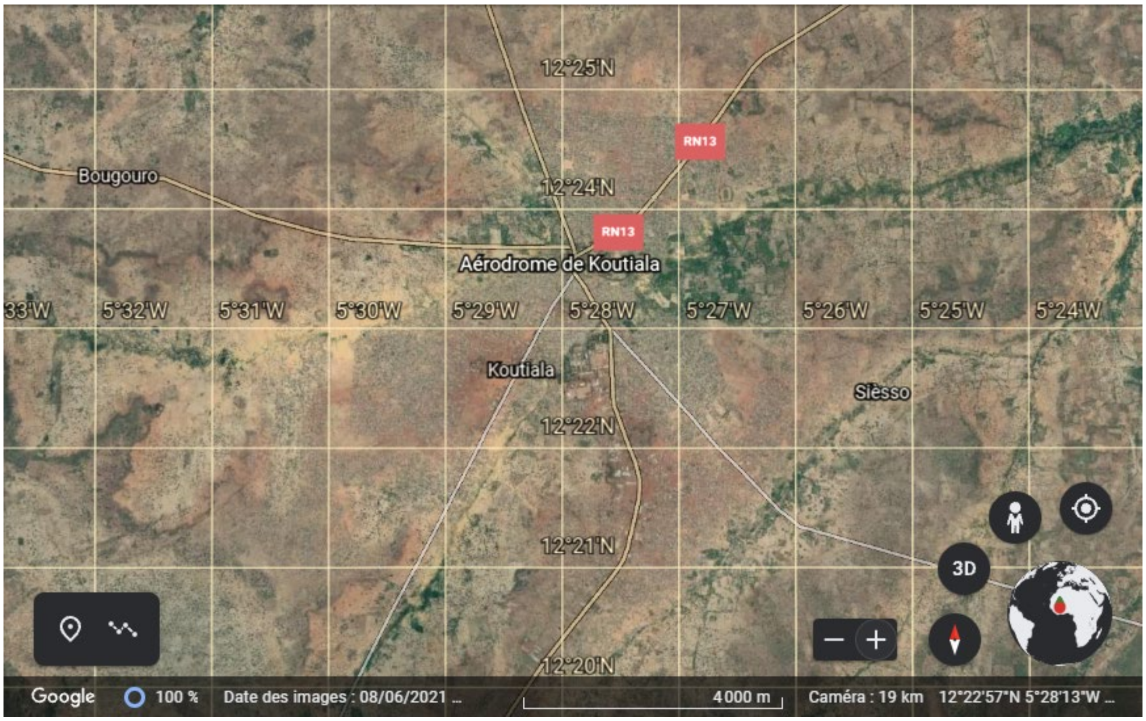


Figure I-b: Geological data generation with RESTscreen

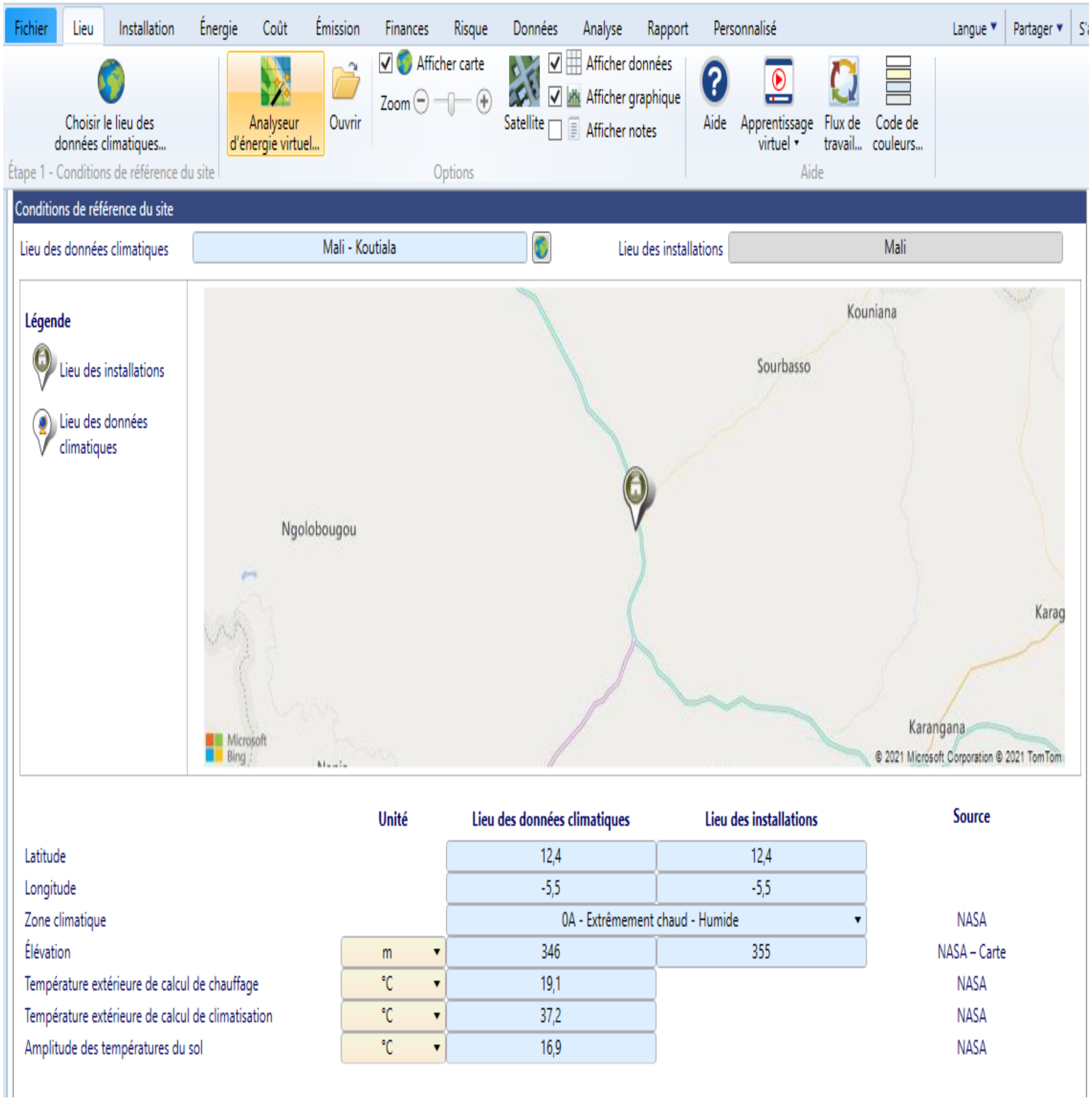


Figure I-c: Geological data generated

RETScreen - Base de données climatiques

Carte | Recherche | Données

Pays		Mali	
Province/État			
Lieu des données climatiques (Voir carte)		Koutiala	
Latitude	°N	12,4	
Longitude	°E	-5,5	**Source**
Zone climatique	0A	Extrêmement chaud - Humide	NASA
Élévation	m	346	NASA
Température extérieure de calcul de chauffage	°C	19,1	NASA
Température extérieure de calcul de climatisation	°C	37,2	NASA
Amplitude des températures du sol	°C	16,9	NASA

Mois	**Température de l'air**	**Humidité relative**	**Précipitation**	**Rayonnement solaire quotidien - horizontal**	**Pression atmosphérique**	**Vitesse du vent**	**Température du sol**	**Degrés-jours de chauffage 18 °C**	**Degrés-jours de climatisation 10 °C**
	°C	%	mm	kWh/m²/j	kPa	m/s	°C	°C-j	°C-j
Janvier	24,0	20,8%	0,62	5,14	97,2	4,3	24,9	0	434
Février	26,9	16,1%	1,40	5,92	97,1	4,4	28,1	0	473
Mars	30,2	20,1%	6,20	6,22	97,0	3,8	31,7	0	626
Avril	32,3	32,8%	27,90	6,32	96,9	3,2	34,3	0	669
Mai	31,5	47,6%	68,51	6,18	97,0	3,3	33,2	0	667
Juin	29,4	59,0%	115,80	5,80	97,2	3,2	30,6	0	582
Juillet	26,9	72,3%	186,62	5,44	97,2	2,8	27,5	0	524
Août	25,6	80,9%	241,80	5,25	97,2	2,5	25,8	0	484
Septembre	25,8	79,6%	153,30	5,53	97,2	2,3	25,9	0	474
Octobre	26,9	67,3%	49,91	5,68	97,2	2,3	27,2	0	524
Novembre	25,9	41,7%	3,60	5,46	97,1	3,1	26,0	0	477
Décembre	23,9	27,6%	0,31	5,14	97,2	4,0	24,3	0	431
Annuel	**27,4**	**47,3%**	**855,97**	**5,67**	**97,1**	**3,3**	**28,3**	**0**	**6 364**
Source	NASA	NASA	NASA	NASA	NASA	NASA	NASA	NASA	NASA
Mesuré à					m	10	0		

Figure I-d: Global irradiation and temperature evolution in the year

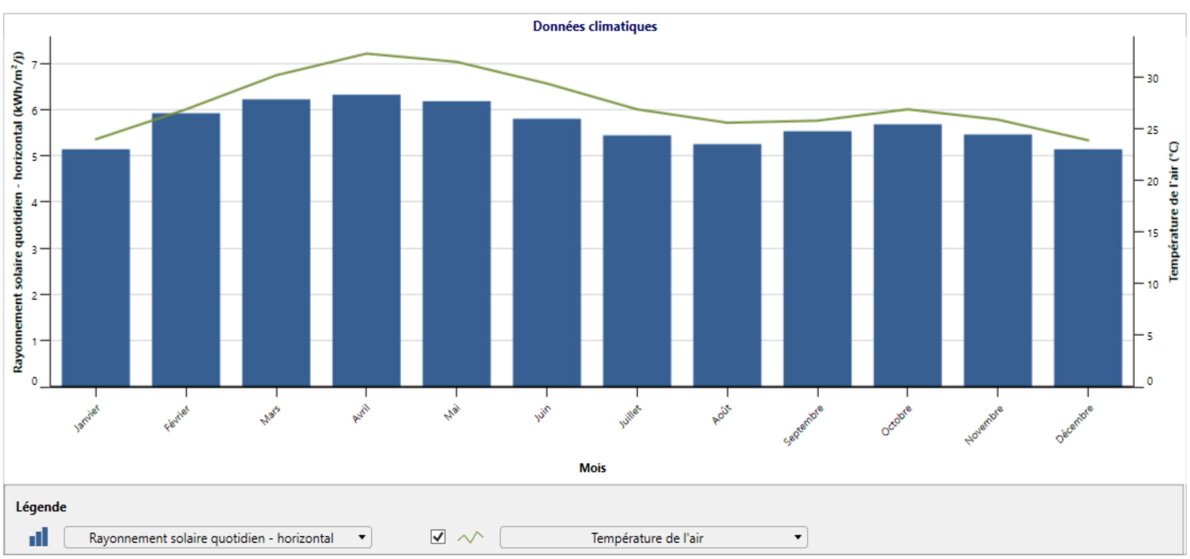


Figure I-e: First step of system designing with PVsyst

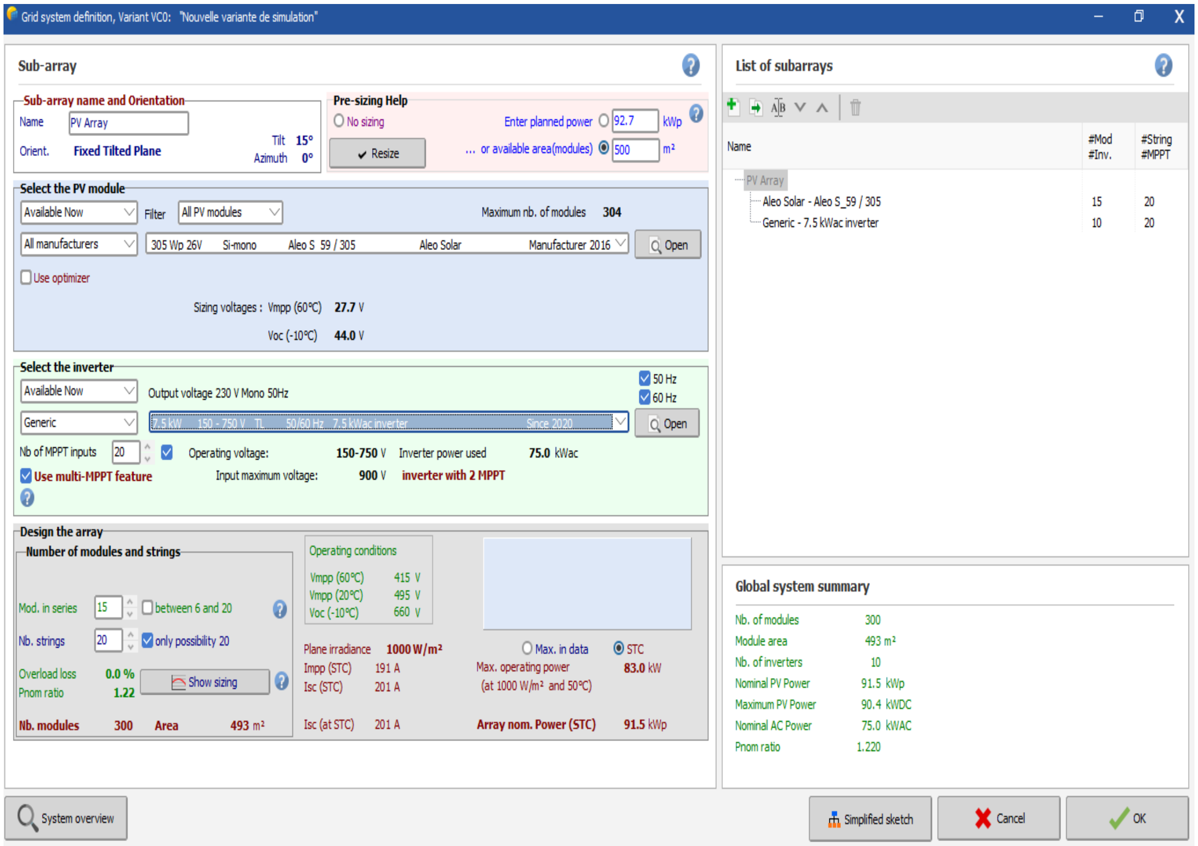


Figure I-f: Simulation result of the system (PVsyst)

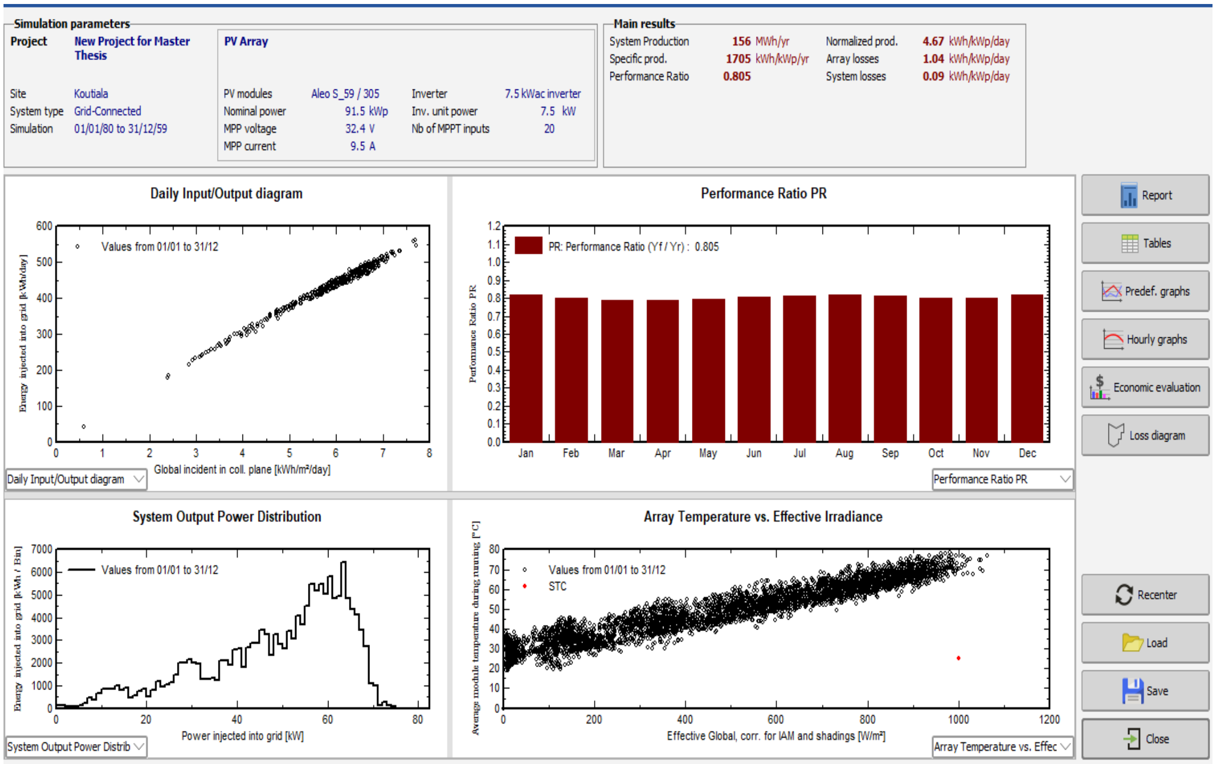
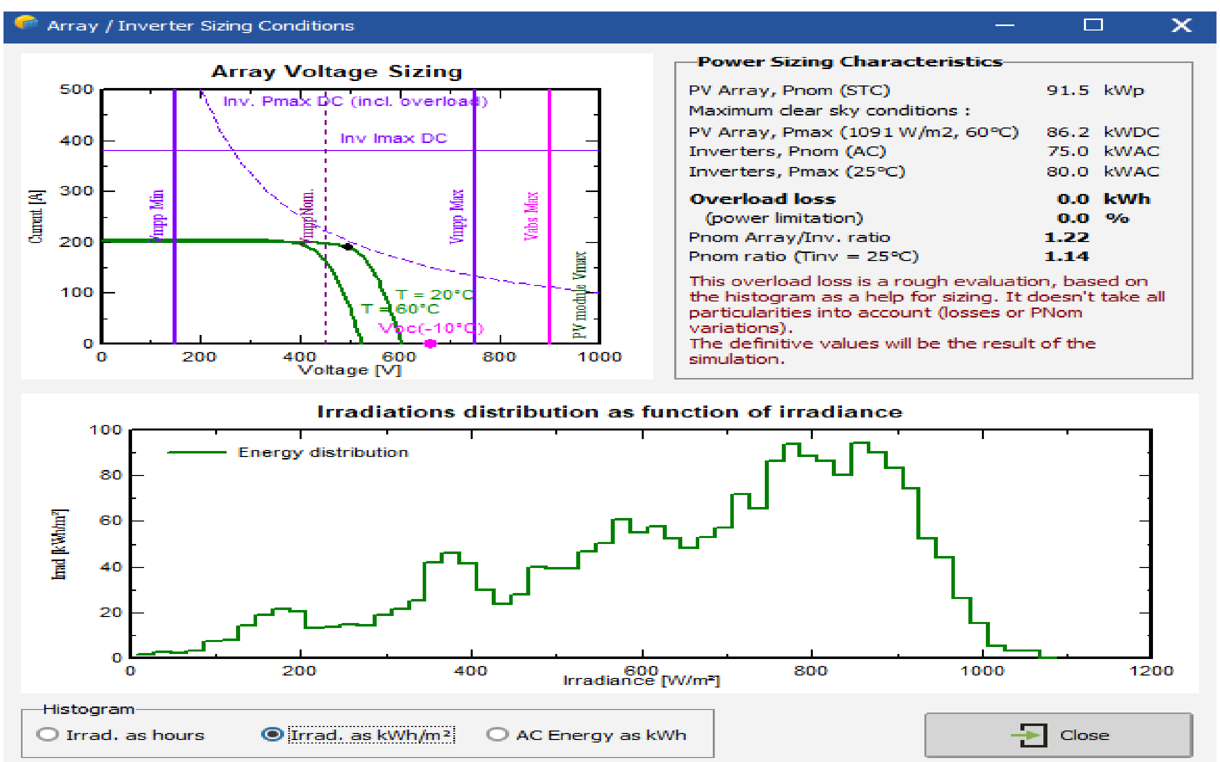


Figure I-g: Power sizing characteristics



Appendix II

Figure II-a: Economic analyze excel program

Data	Agrivoltaic		EOY	Year	CAPEX	Inverter	Elec. Generation	Electricity Price	O&M	Revenue	Net Cash Flow
Real Discount Rate (i_r), %			0	2022							
Study period (N), yrs			1	2023							
Installed capacity, kW			2	2024							
Inverter Useful Life (M), yrs			3	2025							
Data/Derived Variables			4	2026							
Electricty Generation, kWh			5	2027							
Electricity Generation Degradation rate, %			6	2028							
CAPEX, €			7	2029							
Government Subsidy, %		<--Decision	8	2030							
Cash Equivalent of Government Subsidy, €			9	2031							
Installed Cost, €			10	2032							
Specific Installed cost, €/kW			11	2033							
Inverter replacement Cost, €			12	2034							
Annual O&M Cost as percentage of CAPEX, %			13	2035							
Annual O&M, €			14	2036							
Electricity price in Yr 1, €/kWh		<--Decision	15	2037							
Electricity Price Escalation Rate, %			16	2038							
Finacial Indicators			17	2039							
PV Cost			18	2040							
PV Prod			19	2041							
LCOE			20	2042							
NPV			21	2043							
AW			22	2044							
IRR			23	2045							
pv revenu			24	2046							

1. Business model 1:

Figure II-b: Excel program for the business model 1

2			
3	**Data**	grivoltaic Economic analyse	
4	Real Discount Rate (i), %	5,0%	
5	Study period (N), yrs	25	
6	Installed capacity, kW	92,7	
7	Inverter Useful Life (M), yrs	10	
8	**Data/Derived Variables**		
9	Electricity Generation, kWh	150000	
10	Electricity Generation Degradation rate, %	1,0%	
11	CAPEX, €	140 000,00	
12	Government Subsidy, %	0,0%	<--Decision
13	Cash Equivalent of Government Subsidy, €	0	
14	Installed Cost, €	140 000,00	
15	Specific Installed cost, €/kW	1510,25	
16	Inverter replacement Cost, €	8 000,00	
17	Annual O&M Cost as percentage of CAPEX, %	0,5%	
18	Annual O&M, €	700,00	
19	Electricity price in Yr 1, €/kWh	0,1000	<--Decision
20	Electricity Price Escalation Rate, %	2,0%	
21	**Finacial Indicators**		
22	**PV Cost**	(164741,045)	
23	**PV Prod**	€ 1 925 767,99	
24	**LCOE**	(0,09)	
25	**NPV**	€ 74 731,93	
26	**AW**	€ 5 302,41	
27	**IRR**	10%	
28	**PV revenue**	€ 232 524,11	
29	**Pay back period**	17,712	

		Alternativ Agrivoltaic System							
EOY	Year	CAPEX	Gov Sub	Inverter	Elec. Generation	Electricity Price	O&M	Revenue	Net Cash Fl
0	2022	(140000,0)	0,00						(140000,
1	2023				150 000,0	0,1000	(700,00)	15 000,0	14300,
2	2024				148 500,0	0,102	(700,00)	15 147,0	14447,
3	2025				147 015,0	0,104	(700,00)	15 295,4	14595,
4	2026				145 544,9	0,106	(700,00)	15 445,3	14745,
5	2027				144 089,4	0,108	(700,00)	15 596,7	14896,
6	2028				142 648,5	0,110	(700,00)	15 749,5	15049,
7	2029				141 222,0	0,113	(700,00)	15 903,9	15203,
8	2030				139 809,8	0,115	(700,00)	16 059,8	15359,
9	2031				138 411,7	0,117	(700,00)	16 217,1	15517,
10	2032			(8000,00)	137 027,6	0,120	(700,00)	16 376,1	7676,
11	2033				135 657,3	0,122	(700,00)	16 536,6	15836,
12	2034				134 300,7	0,124	(700,00)	16 698,6	15998,
13	2035				132 957,7	0,127	(700,00)	16 862,3	16162,
14	2036				131 628,2	0,129	(700,00)	17 027,5	16327,
15	2037				130 311,9	0,132	(700,00)	17 194,4	16494,
16	2038				129 008,8	0,135	(700,00)	17 362,9	16662,
17	2039				127 718,7	0,137	(700,00)	17 533,0	16833,
18	2040				126 441,5	0,140	(700,00)	17 704,9	17004,
19	2041				125 177,1	0,143	(700,00)	17 878,4	17178,
20	2042			(8000,00)	123 925,3	0,146	(700,00)	18 053,6	9353,
21	2043				122 686,0	0,149	(700,00)	18 230,5	17530,
22	2044				121 459,2	0,152	(700,00)	18 409,2	17709,
23	2045				120 244,6	0,155	(700,00)	18 589,6	17889,
24	2046				119 042,1	0,158	(700,00)	18 771,7	18071,
25	2047				117 851,7	0,161	(700,00)	18 955,7	18255,

Figure II-c: Excel program for the business model 2

2		
3	Data	grivoltaic Economic analyse
4	Real Discount Rate (i), %	5,0%
5	Study period (N), yrs	25
6	Installed capacity, kW	92,7
7	Inverter Useful Life (M), yrs	10
8	Data/Derived Variables	
9	Electricity Generation, kWh	150000
10	Electricity Generation Degradation rate, %	1,0%
11	CAPEX, €	140 000,00
12	Government Subsidy, %	0,0% <--Decision
13	Cash Equivalent of Government Subsidy, €	0
14	Installed Cost, €	140 000,00
15	Specific Installed cost, €/kW	1510,25
16	Inverter replacement Cost, €	8 000,00
17	Annual O&M Cost as percentage of CAPEX, %	0,5%
18	Annual O&M, €	700,00
19	Electricity price in Yr 1, €/kWh	0,1500 <--Decision
20	Electricity Price Escalation Rate, %	0,0%
21	Finacial Indicators	
22	PV Cost	(164741,045)
23	PV Prod	€ 1 925 767,99
24	LCOE	(0,09)
25	NPV	€ 131 073,02
26	AW	€ 9 299,95
27	IRR	14%
28	PV revenue	€ 288 865,20
29	Pay back period	14,258

			Alternativ Agrivoltaic System						
EOY	Year	CAPEX	Gov Sub	Inverter	Elec. Generation	Electricity Price	O&M	Revenue	Net Cash Fl
0	2022	(140000,0)	0,00						(140000,
1	2023				150 000,0	0,1500	(700,00)	22 500,0	21800,
2	2024				148 500,0	0,150	(700,00)	22 275,0	21575,
3	2025				147 015,0	0,150	(700,00)	22 052,3	21352,
4	2026				145 544,9	0,150	(700,00)	21 831,7	21131,
5	2027				144 089,4	0,150	(700,00)	21 613,4	20913,
6	2028				142 648,5	0,150	(700,00)	21 397,3	20697,
7	2029				141 222,0	0,150	(700,00)	21 183,3	20483,
8	2030				139 809,8	0,150	(700,00)	20 971,5	20271,
9	2031				138 411,7	0,150	(700,00)	20 761,8	20061,
10	2032			(8000,00)	137 027,6	0,150	(700,00)	20 554,1	11854,
11	2033				135 657,3	0,150	(700,00)	20 348,6	19648,
12	2034				134 300,7	0,150	(700,00)	20 145,1	19445,
13	2035				132 957,7	0,150	(700,00)	19 943,7	19243,
14	2036				131 628,2	0,150	(700,00)	19 744,2	19044,
15	2037				130 311,9	0,150	(700,00)	19 546,8	18846,
16	2038				129 008,8	0,150	(700,00)	19 351,3	18651,
17	2039				127 718,7	0,150	(700,00)	19 157,8	18457,
18	2040				126 441,5	0,150	(700,00)	18 966,2	18266,
19	2041				125 177,1	0,150	(700,00)	18 776,6	18076,
20	2042			(8000,00)	123 925,3	0,150	(700,00)	18 588,8	9888,
21	2043				122 686,0	0,150	(700,00)	18 402,9	17702,
22	2044				121 459,2	0,150	(700,00)	18 218,9	17518,
23	2045				120 244,6	0,150	(700,00)	18 036,7	17336,
24	2046				119 042,1	0,150	(700,00)	17 856,3	17156,
25	2047				117 851,7	0,150	(700,00)	17 677,8	16977,