MASTERTHESIS

Development and analysis of cost optimized system scenarios for hydrogen production with agrivoltaics and wind energy in India

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Abstract

Green hydrogen and agrivoltaics technological development and uptake will happen rapidly in India in the coming years. Combination of solar energy and wind energy with auxiliary grid has been in use since many years for green hydrogen production. This study aims to now understand the feasibility of green hydrogen generation with agrivoltaics. Two objectives were defined for this study i.e, investigation of current status of use of hydrogen in the domain of agriculture and optimization of system design to minimize the levelized cost of hydrogen (LCOH) using the software MHOGA PRO+.

The grid, wind energy and battery storage were considered as an auxiliary source wherever necessary. Four different agrivoltaic system types i.e., overhead static – arable farming, overhead static – permanent crops, interspace vertical and overhead dynamic were simulated in three configurations i.e, grid, grid to sell and off-grid to analyze and evaluate the feasibility of individual configurations for hydrogen production.

Literature review was conducted to understand the synergies and extent of use of green hydrogen directly and indirectly in the field of agriculture. The most studied use cases for green hydrogen in agriculture were found to be source of energy for agricultural activities and machinery, use of the by-product oxygen in fish breeding and use of green ammonia as fertilizer.

Interspace vertical system type was found out to be the most suitable system in this context for cost-efficient production of hydrogen with agrivoltaics. Interspace vertical with the auxiliary grid to sell is the most suitable configuration with a LCOH of 3.67 Eur/kg or 328 Rs/kg. It drops to 2.80 Eur/kg or 250 Rs/kg in 2050.

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1 Introduction

1.1 Motivation

India aims on becoming energy independent by 2047 and achieving net zero emissions by 2070. (National portal of India, 08/05/204) Hydrogen will play a key role in this transition. Hydrogen can be utilized for long-duration storage of renewable energy, replacement of fossil fuels in industries like aviation and marine transportation, and potentially also for decentralized power generation. (National portal of India, 08/05/204) According to an analysis done by The Energy and Resource Institute in India (TERI), India will see a 5-fold surge in demand of hydrogen by 2050. Presently annual demand of hydrogen in country is around 6 million tons (Mt) and is estimated to reach around 28 Mt by 2050. Grey hydrogen won't be able to fulfill such a massive demand as India is witnessing decline in fossil fuel production. Imported natural gas prices in India are 3–4 times the prices seen in other parts of the world, such as the United States of America. Reasons for this difference could include higher import costs, different taxation policies, and less domestic production compared to the USA. On the other hand, India has some of the cheapest renewable generation costs in the world. Hence by 2050, nearly 80% of India's hydrogen is projected to be 'green' – produced by renewable electricity and electrolysis. (Will Hall, 2020)

The Indian government launched a National Hydrogen Mission in 2023 to promote the development of green hydrogen infrastructure in India. The government in the beginning of 2023 announced $2 billion (1.87 billion Eur according to the conversion rate shown in Table 13) for the "National green hydrogen mission". (Sidhartha Harichandan, Sanjay Kumar Kar, Prashant Kumar Rai, 2023) This mission aims to build capabilities to produce at least 5 million metric ton (MMT) of green hydrogen per annum by 2030, with potential to reach 10 MMT per annum with growth of export markets. It also aims to make India a leader in technology and manufacturing of electrolysers and other enabling technologies for green hydrogen. (Ministry of New and Renewable Energy [MNRE], 2023) There will be an incentive of a maximum of Rs 50, Rs 40 and Rs 30 per kg of hydrogen produced (0.56 Eur/kg, 0.45 Eur/kg and 0.34 Eur/kg respectively according to the conversion rate shown in Table 13) for the first, second and third year of supply to promote the uptake of green hydrogen technology by the industry. Heavy manufacturing industries will continue to be India's major consumer of hydrogen through 2050, accounting for 80% of overall demand. India plans to completely replace imported ammonia-based fertilizer with domestically manufactured environmentally friendly green ammonia-based fertilizers by 2035. India may save one trillion rupees annually (11.2 billion Eur annually according to the conversion rate shown in Table 13) in fertilizers subsidies if the country switched to green ammonia as a fertilizer feedstock. All state-owned oil and gas corporations that engage 40 ships for fuel transportation must additionally employ at least one green hydrogen fueled ship fueled by 2030. (Sidhartha Harichandan, Sanjay Kumar Kar, Prashant Kumar Rai, 2023) Hence there is a surge in green hydrogen projects around the country.

If we consider that 100% of this demand of hydrogen in 2050 is being fulfilled by the hydrogen produced through electrolysis than it would be requiring around 1500 Terawatt hour (TWh) of electricity which is more than the total grid electricity produced in India today. (Rahul Kumar Singh, Dr. Nirlipta Priyadarshini Nayak, 2023) Hence, renewable energy integration will be crucial to meet this huge demand. India currently has the fourth largest installed capacity of wind in the world at 43.7 GW (as of June 2023). (Press Information Bureau, 2023, 2024b) Most of this capacity is available in nine major wind-rich states (Andhra Pradesh, Gujarat, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Rajasthan, Tamil Nadu and Telangana). Similarly, India stands fifth in solar PV deployment across the globe as of end of 2023. (Press Information Bureau, 2023) Solar power installed capacity has reached around 70.1 GW (as of June 2023). (Press Information Bureau, 2024a) India's technical potential of onshore wind and solar is only about three times that of India's forecasted 2050 demand which is a cause for concern. (Will Hall, 2020) Land is another concern for building solar parks and installing wind turbines. The country's ever growing population makes it highly challenging for the government to address the water and land-energy nexus issues. (Sidhartha Harichandan, Sanjay Kumar Kar, Prashant Kumar Rai, 2023)

Integrated PV like agrivoltaics presents itself as a solution here to unlock additional avenues of energy generation to complement the traditional sources to achieve the 2047 target of energy independence and the national hydrogen mission targets for 2030. Agrivoltaics and other integrated PV applications in a rural and urban context will play a key role in India's energy transition. Agrivoltaics plays a unique role in this sphere as not only will it be an additional energy source for the future, but it will also contribute to the Indian economy by helping farmers protect their yield against the threats of climate change and have additional sources of income through land lease, sale of electricity, hydrogen, etc. Hence, government of India is also actively promoting the uptake of agrivoltaics amongst farmers. PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan) Scheme was launched in 2019 aimed at ensuring energy security for farmers in India. Component A under this scheme targets at setting up of 10 GW of decentralized grid connected renewable energy power plants of capacity 500 kW to 2 MW on barren land. (National portal of India, 2019) It provides a procurement-based incentive as the electricity generated will be purchased by local distribution companies at pre-fixed tariff. Agrivoltaics potential for India estimated through a Fraunhofer ISE project in collaboration with Indian partners called I-Sun lies in the maximum and minimum range of 3 and 13 TWp depending on the crops and the specific system orientation. Hence, an uptake in the deployment of agrivoltaics is expected soon.

Electrolysis requires around 9 liters of fresh water to produce one kg of hydrogen. India's entire hydrogen demand with electrolysis would require around 54 million cubic meter today, rising to approximately 270 million cubic meters by 2050. India's total usable water supply is between 700 billion cubic meter and 1,200 billion cubic meter in total. (Will Hall, 2020) Water consumption for electrolysis appears to be a minor issue but according to a report by the National Institute for Transforming India (NITI Aayog) in 2018, 21 major cities are already reaching zero groundwater levels in 2020 – affecting access to water for 100 million people. Rainwater harvesting can be integrated synergistically with agrivoltaics installations. It has been so far explored as an option for water storage for irrigation/frost prevention purposes during dry seasons. A synergy would need to be established between the water demand for current existing use cases and the additional demand expected from green hydrogen production by water electrolysis method. Agrivoltaics with its rainwater harvesting potential could help lessen the stress from this inevitably rising demand for water.

Hence the purpose of this study is to investigate the synergy of agrivoltaics and hydrogen production. The aim is to understand the feasibility of hydrogen production with agrivoltaics and wind energy in an Indian context. Framework conditions for green hydrogen production will be analyzed considering different scenarios to propose the most optimum techno-economic system configuration for hydrogen production. The grid, wind energy and battery storage will be considered as an auxiliary source wherever necessary. Four different agrivoltaic system types – overhead static – arable farming, overhead static – permanent crops, interspace vertical and overhead dynamic will be simulated to evaluate the feasibility of individual configurations for hydrogen production.

1.2 Structural design and problem statement

Section 1 introduces the study and describes the motivation for the study. Objectives of the study are described in this section. Section 2 provides a brief overview of agrivoltaics and describes the system configurations considered for this study. Relevant case studies and applications of hydrogen in agriculture are introduced in the second section. Section 3 describes the simulation methodology. Input parameters and variables set in the simulation software have been documented in that section. Simulation results have been analyzed and discussed in section 4.

Objectives of this study are:

Objective 1: Investigation of current status of use of hydrogen in the domain of agriculture.

Objective 2: Optimization of system design to minimize the levelized cost of hydrogen (LCOH) using the software MHOGA PRO+.

- 2.1 To simulate and analyse three different types of hydrogen production configurations – grid hydrogen, green hydrogen with auxiliary grid to sell excess electricity generated, off-grid green hydrogen.
- 2.2 To analyze the feasibility of the four different agrivoltaic system types for cost-efficient uniform hydrogen production.
- 2.3 Sensitivity analysis for future cost projection of hydrogen for the years 2040 and 2050.

Figure 1 shows the layout of the system design used in the simulations and Table 1 gives an overview of the different simulations considered in this study.

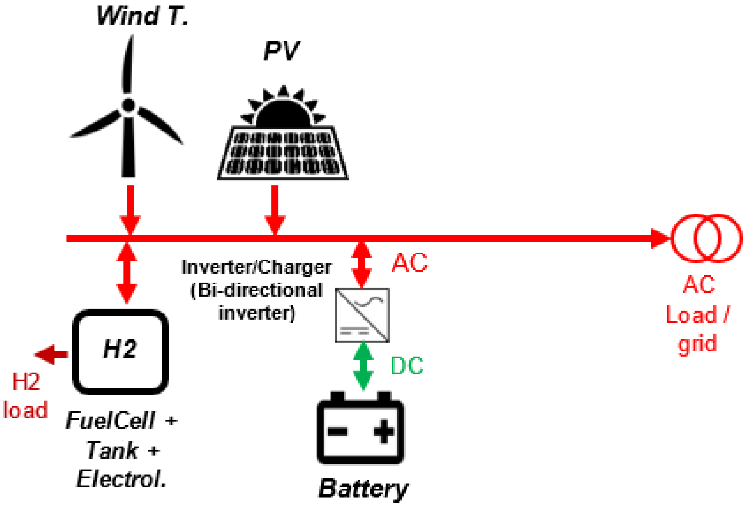


Figure 1: Pictorial representation of simulated system components; Source: MHOGA software snapshot

Table 1: Representation of simulation configurations; Source: Own creation

Simulation No.	**Type of agrivoltaics**	**Use of Grid**		**Sensitivity Analysis – Cost projections**		
		Buy from grid	**Sell to grid**			
1.1	Overhead static - arable farming	✓	✓	Base	2040	2050
1.2		×	✓			
1.3		-	-			
2.1	Overhead static - permanent crops	✓	✓			
2.2		×	✓			
2.3		-	-			
3.1	Interspace vertical	✓	✓			
3.2		×	✓			
3.3		-	-			
4.1	Overhead dynamic	✓	✓			
4.2		×	✓			
4.3		-	-			

2 Literature review

This section introduces the concept of agrivoltaics and describes the different system configurations considered for this study. Objective 1 of this study is the investigation of current status of use of hydrogen in the domain of agriculture. Results of the literature review done in this regard have been presented in this section.

2.1 Introduction to agrivoltaics

Agrivoltaics is the simultaneous use of land for agricultural food production and PV electricity production. In this way, agrivoltaics increases land efficiency and enables the expansion of PV while preserving arable land for agriculture. (Fraunhofer ISE, 2021) Prof. Adolf Goetzberger, founder of Fraunhofer ISE, and Dr. Armin Zastrow were the first to propose this kind of dual land use with their 1981 article "Kartoffeln unter dem Kollektor" (potatoes under the collector). (Fraunhofer ISE, 2022) They wanted to refute through this study the prejudices in 1981 that larger solar systems have life threatening effects and lead to destruction of the landscape. They intended to prove that solar farms and agriculture do not necessarily have to be in opposition to each other but can go hand in hand with each other. Hence, they proposed a system which was 2m high from the ground and distance between the rows of PV modules was three times the height, so that the irradiation will be uniformly distributed on the ground. They observed in the two experiments conducted that 62% and 71% of the global irradiation is obtained under the PV modules with pitch distances between the rows of 3m and 4m respectively compared to the reference field with no modules. (Adolf Goetzberger, 1981) In 2014, the innovation group APV-RESOLA ("Agrivoltaics: contribution to resource efficient land use") took this idea and implemented it in a pilot project at Heggelbach farm near Lake Constance in Germany. This project investigated the economic, technical, social and environmental aspects of agrivoltaics technology in real-world conditions, with the aim of demonstrating its basic feasibility. (Fraunhofer ISE, 2022) Agrivoltaics has now developed around the world in different configurations and types and as end of 2021, installed capacity around the globe is around 14 GWp.

Agrivoltaics offers numerous benefits including the following: (Fraunhofer ISE, 2022):

- Protection against storm, hail, frost, and drought damage
- Reducing irrigation demand by up to 20 %
- Collecting rainwater for irrigation
- Reducing wind erosion
- Using the PV system's mounting system to attach protective nets or sheets
- Optimizing the available light for crops
- Increasing PV module efficiency through improved convective cooling
- Diversification of farmers income sources

The ever-increasing rise in mean temperatures due to global warming has its effect directly on the crops as well as indirectly via the changing climatic patterns. Drought, hail, strong winds and heavy rainfall can impact crop growth. Agrivoltaics presents itself as a solution to not only mitigate these adverse effects but also provides additional benefits with it as enlisted above. Agrivoltaics can contribute to improving the rural economy by adding additional sources of income through the sale of electricity or leasing of land. The Indian government in 2016 had set a goal of doubling farmers income. Agrivoltaics could play a key role in achieving such a target.

Use of agrivoltaics in combination with another rapidly emerging technology of green hydrogen could prove to be mutually beneficial for the development and uptake of both technologies. Hence, this study aims to study the potential synergies and framework conditions between these technologies.

2.2 Description of considered system types

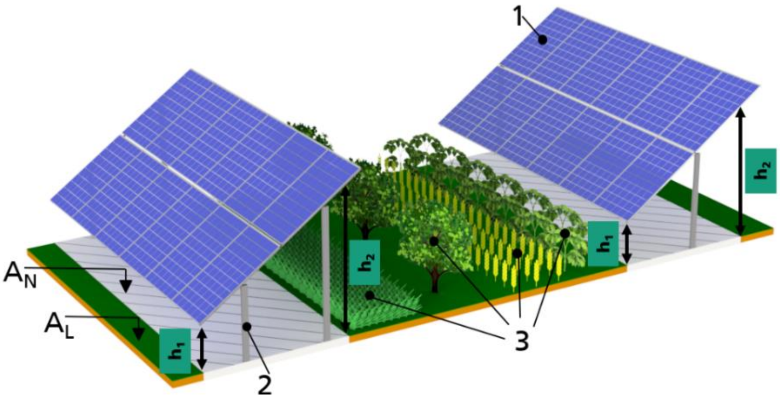
DIN Spec 91434 was developed in Germany to outline the requirements of designing and assessing an agrivoltaics system. DIN or Deutsches Institut für Normung is a standardization body that published norms that outline the key performance indicators necessary to classify an agrivoltaics system. This was done to enable a proper uptake of the technology in Germany. It was developed by a multi varied group of different stakeholders, directly or indirectly involved in the field of agrivoltaics. According to the DIN standards, agrivoltaic systems can be divided into two main types (DIN, 2021):

- Interspace with a clear height < 2.1 m
- Overhead with a clear height > 2.1 m

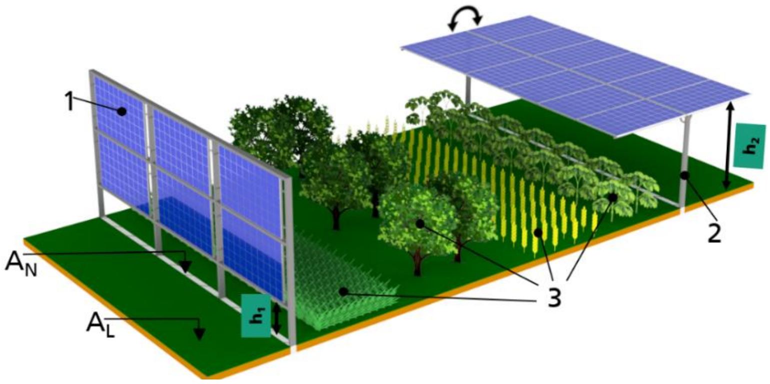
Clear height is defined as clear vertical area between the base of the agricultural land and the lower edge of the lowest structural element which is under self-weight deformation. (DIN, 2021) It is shown as h1 in Figure 2. Different systems and their applicability in this study have been briefly introduced in this chapter with the help of few example case studies.

2.2.1 Interspace agrivoltaics

Interspace agrivoltaic systems can be identified by the crops growing in between the module rows. They can be further divided into three main types as shown in Figure 2 static systems (a), vertically mounted static systems (b) and tracking systems (b).



(a)



(b)

Legend:

A_L - Cultivatable agricultural areas

A_N - Uncultivatable agricultural area

H_1 - Clearance height below 2.10 m

H_2 - Clearance height above 2.10 m

1 - Examples of solar modules

2 - Mounting structure

3 - Examples of crops

(c)

Figure 2: Illustration of the interspace systems proposed in the DIN SPEC (a) Typically mounted static system, (b) vertically mounted static system (left) and dynamic system (right), (c) Legend ©Fraunhofer ISE

Fraunhofer ISE analysis has shown that the power density for such systems is in the range of 250-350 kWp/ha. They have a comparatively higher area loss of 15 %, as the space under the PV modules is not considered to be agriculturally usable according to the DIN standards. Agriculturally unusable area (shown as A_N in Figure 2) is limited to the area of the installation and areas that are no longer available for conventional agriculture in the course of farming the field, in accordance with the agricultural cultivation proposal. (DIN, 2021) Hence this system configuration is not considered in this study. Sun tracking systems on the other hand can be programmed to dynamically controlling the light availability either for the modules or for the crops. This means the modules can prioritize either electrical yield (sun tracking) or agricultural yield (sub-optimal sun tracking). Hence the overhead variation of this configuration has been considered for this study. It has been described below. Interspace vertical system configuration though has been considered for this study.

2.2.1.1 Interspace vertical system

Next2Sun GmbH in Germany pioneered this type of system. This company has already implemented several demonstration plants and commercial systems worldwide, with the 4.1 MWp system in Donaueschingen, Germany being the largest project which is shown in Figure 3. The crops grown were meadows for hay and silage. (next2sun, 2024b)

Figure 3: 4.1 MWp vertical E-W plant in Donaueschingen-Aasen ©Next2Sun

Two rows of bifacial modules in 2P orientation are mounted vertically or with a tilt angle of 90° facing east and west direction. Area loss of agriculturally usable area is much less compared to the other interspace system configurations. Next2Sun claim that up to 90% of the solar park area can still be used for agriculture. (next2sun, 2024a) This system can also serve as a windbreaker and protect the plants from high wind speeds. It also has a positive effect on evaporation and reduces the risk of wind erosion. (Fraunhofer ISE, 2022) Another advantage is that the homogeneity of the rainwater is only slightly affected by the system. (Riaz, Muhammad Hussnain Imran, Hassan et al., 2021) Bruhwyler in their study of a 100 kWp vertical agrivoltaics system in drought stricken area in Chile observed water savings of up to 1410 m3/ha mainly due to the reduced irradiation combined with windbreak effects. (Roxane

Bruhwyler, Hugo Sánchez,Carlos Meza, Frédéric Lebeau, Pascal Brunet, Gabriel Dabadie, Sebastian Dittmann, Ralph Gottschalg, Juan Jose Negroni, 2023)

Such a vertical orientation also helps the modules to maximize the PV yield during the morning and afternoon hours when the sun is closer to the horizon. This means that daily power generation profiles differ from typical south-facing systems, with two peaks, one in the morning and one in the afternoon as shown in Figure 4. This unique characteristic with respect to time can be beneficial when the generated electricity is traded in spot markets. In addition, the system could also benefit grid stability by boosting PV production during hours when it is usually limited. Feasibility of having these two peaks for uniform green hydrogen production throughout the day requires further analysis. Hence this system has been considered for this study.

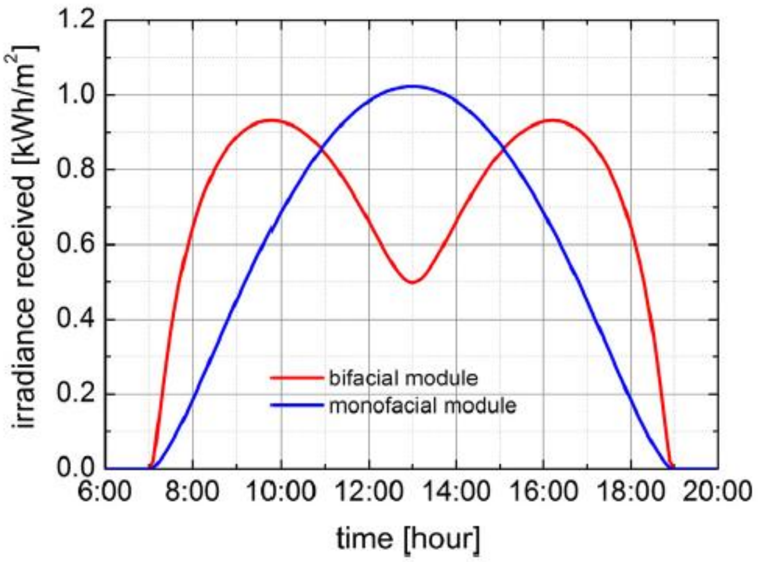


Figure 4: Daily irradiation curve for a south-facing monofacial module (blue) and an east-facing bifacial module (red), Source: (Guo, Siyu, Walsh, Timothy Michael & Peters, 2013)

System configuration similar to the one shown in Figure 3 has been considered in this study with pitch distance of 10 m and clear height of 1.5 m.

2.2.2 Overhead agrivoltaics

Overhead agrivoltaic systems can be identified by the crops growing below the module rows. Their clear height varies between 2 and 6 m. (Fraunhofer ISE, 2022) Such elevated mounting structures increase the CAPEX in comparison to interspace systems. Despite their higher cost, they offer the least hinderance to the agricultural activities below. Fraunhofer ISE has conducted many studies simulating the effect of PV modules on the light availability for the crops in between and/or below the modules. PAR or photosynthetically active radiation and coefficient of variation are two factors that are usually measured here. PAR is indicative of the light available for photosynthesis for plants in between and/or below the PV modules. Similarly, coefficient of variation denotes the per row variation in the irradiation values in between and/or below the modules. Fraunhofer ISE studies have shown that PAR is comparatively higher, and coefficient of variation is lower for overhead systems to interspace systems for respective pitch distances. Hence this system configuration has been considered in this study. These systems can be further distinguished into four main categories: static system over arable land or fruit trees/berries, dynamic system over arable land or fruit trees/berries as seen by the illustration in Figure 5 and examples in Figure 6 and Figure 7.

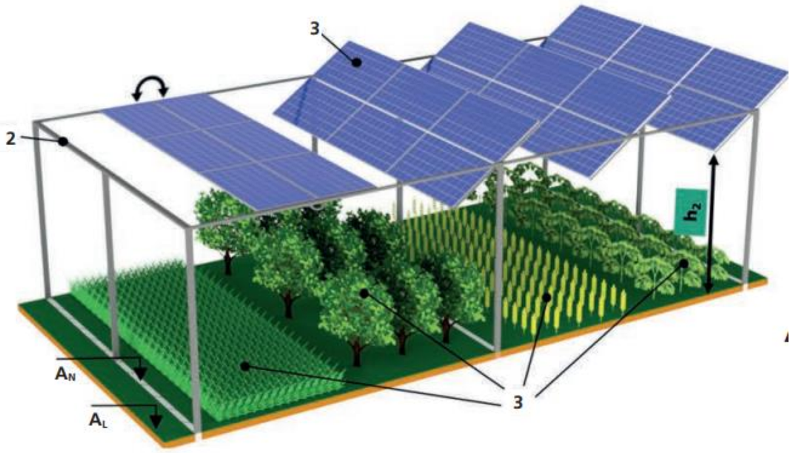


Figure 5: Illustration of the overhead PV system category I © Fraunhofer ISE

Figure 6: Overhead static system over berries in Netherland © BayWa r.e. and GroenLeven

Figure 7: Overhead dynamic system in Italy © REM Tec

2.2.2.1 Overhead static – arable farming system

Static systems are overhead systems where the PV modules are fixed for a specific tilt angle. This angle can be optimized for either the light availability for the crops underneath or the electric yield of the modules. Normally it is optimized for the PV yield as the research on optimum light requirement for crops and the impact of PV module on the light availability is still at a nascent stage. This configuration has higher PAR and lesser coefficient of variation compared to interspace system as explained previously but it also has a comparatively higher CAPEX. Its feasibility for cost-efficient uniform hydrogen production requires further analysis. It is also a widely used agrivoltaic system configuration and hence, it has been considered for this study.

The 194 kWp pilot plant by Fraunhofer ISE in Heggelbach, Germany is shown in Figure 8. It deviates from the purely southern orientation, which significantly improves the light homogeneity on the ground. (Trommsdorff, Max, Kang, Jinsuk et al., 2021) This system has been installed with a clear height of 5.5 m and a row-to-row pitch distance of 9.5 m. The use of bifacial modules partially compensated for the electrical losses caused by the deviation, with the bifacial gain being approximately 8.7%. (Trommsdorff, Max, Kang, Jinsuk et al., 2021) Bifacial gain indicates the additional energy yield obtained from the rear side of the bifacial modules. As the modules are mounted at a higher clear height, bifacial modules are utilized in agrivoltaics to optimize the energy yield as evident from the results of this pilot project in Germany. Bifacial modules are considered for all system configurations in this study with a bifaciality factor of 0.7 (Jinko Solar, 2024). Bifaciality factor is the ratio of the nominal efficiency of the rear side of the modules to the front side. (PVsyst, 2024) Similar system facing south with pitch distance of 8.5 m and clear height of 3 m has been considered in this study.

Figure 8: Pilot plant in Heggelbach, Germany ©BayWa r.e.

2.2.2.2 Overhead static – permanent crops system

Static systems over fruit trees or berries are also referred to as orchard-agrivoltaics. The modules partially replace plastic foils or hail nets that have already been attached (Fraunhofer ISE, 2020). The modules must be installed exactly above the trees or shrubs, i.e., clear height and azimuth of the system are dictated by the arrangement of the plants. Semi – transparent modules are hence used widely for these systems. Semi-transparent panels allow for greater light intensity to the plants compared to the opaque panels, while not increasing the soil/substrate or air temperatures, which can be beneficial to plants. (Mark Uchanski, Thomas Hickey, Jennifer Bousselo and Kurt L. Barth, 2023) This study compares the four system configurations from the perspective of their techno-economic feasibility with respect to uniform energy generation with green hydrogen production and not directly their light availability for the crops growing in the system. Hence, same type of opaque modules are considered for all system configurations.

Such systems with a total output of up to 1,700 kilowatts peak (kWp) are to be erected at five locations in Baden-Württemberg, Germany in a project called ‘Modellregion – Agrivoltaics for Baden Württemberg’, led by Fraunhofer ISE. (Fraunhofer ISE, 2023) Figure 9 shows a 239 kWp system installed above an apple orchard in Kressbronn, Germany. Two semi-transparent module types with transparency 51% and 40% are compared with each other. Preliminary results by Fraunhofer ISE for the first year showed higher apple yields under the agrivoltaic system compared to the reference. Higher redness was interestingly observed in the apples under the 40 % transparency compared to the 51 % transparency for the first year.

Figure 9: Apple orchard agrivoltaic system in Kressbronn, Germany ©Fraunhofer ISE

The east-west orientation of this system similar to the interspace vertical system described previously is interesting from the perspective of uniform hydrogen production. The overhead configuration compared to interspace has a higher power density along with a comparatively higher CAPEX. This configuration has hence been considered to analyse the interplay between these two variables for economically feasible uniform hydrogen production. System like the one shown in Figure 9 with opaque modules, pitch distance of 7 m and clear height of 3 m has been considered in this study.

2.2.2.3 Overhead dynamic system

Overhead dynamic system can be identified by agrivoltaic system with 1-axis and 2-axis tracking mechanisms. Tracking systems provide the possibility of dynamically controlling the light availability as explained in 2.2.1. Green hydrogen production would require a uniform supply of energy for constant production. A dynamic system can retrospectively ensure this condition. Fraunhofer ISE analysis shows that the tracking mechanisms can increase the CAPEX by a factor of 41% compared to static systems. Hence, this configuration was also chosen for this study to analyse its feasibility for cost-efficient uniform hydrogen production and significance of the higher CAPEX.

Figure 10 shows the overhead dynamic system from the EU project HyPErFarm in Straßkirchen, Germany. One of the goals of this project was to develop a material efficient single axis tracked system. The system includes a one-axis tracking mechanism, and the pilot installation covers an area of approximately 0.6 ha (91 x 66 m), with ~0.5 ha designated for agricultural practice. The pilot system has a capacity of 302.4 kWp and is equipped with 672 bifacial PV-modules at a clear height of 4.5 m. (HyPErFarm, 2022). Similar system with pitch distance of 7 m and clear height of 3 m has been considered in this study.

Figure 10: 302.4 kWp 1-axis tracking system in Straßkirchen, Germany ©Fraunhofer ISE

2.3 Description of considered system combination

Hydrogen can be produced from different feedstocks such as fossil fuels, nuclear, biomass and water, or from combination of them. (S. Safari, Farbod Esmaeilion, A. Rabanian, D. H. Jamali, S. Negi, 2024) Renewable sources amongst these are the focus of this study. The technology of water decomposition based on renewable energy sources, to produce hydrogen, can be achieved by different processes - photochemical; photocatalysis, photo-electrolysis, bio-photolysis, thermolysis, thermochemical, steam electrolysis, hybrid processes, and concentrated solar energy. Electrolyser powered with green energy sources has become the most appropriate commercial instrument for hydrogen productivity and storage. (Mohamed Benghanem, Adel Mellit, Hamad Almohamadi, Sofiane Haddad, Nedjwa Chettibi, 2023)

The renewable energy source and water electrolyser are the two key components of a green hydrogen system. During water electrolysis, water decomposes into hydrogen and oxygen under electricity using an electrolyser. (Mohamed Nasser, Tamer F. Megahed, Shinichi Ookawara, Hamdy Hassan, 2022) Currently, the most widely available electrolysis technologies are alkaline and proton exchange membrane electrolysis. (Rahul Kumar Singh, Dr. Nirlipta Priyadarshini Nayak, 2023) Alkaline electrolysis is the most mature technology, having been used in the fertilizer and chlorine industries since the 1920s. (Will Hall, 2020) Fraunhofer ISE conducted a study to examine production, transport and supply costs of key Power-to-X products. Polymer electrolyte membrane (PEM) electrolyser was selected in this study, due to its high dynamic response to variable input power from wind and solar and its high-pressure production of hydrogen. (Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023) PEM are expected to be installed more frequently in the future as they have the highest hydrogen production efficiency among the currently established technologies. (Takuma

Otaki, 2023) Hence, PEM electrolyser was also chosen for this study. Electrolyser technical parameters have been enlisted in section 3.2 in Table 9 .

PV or specifically agrivoltaics has been selected as primary source for green hydrogen production in this study. PV/H2 system is the most used method for green hydrogen production because of its cost, performance, and feasibility. (Mohamed Benghanem, Adel Mellit, Hamad Almohamadi, Sofiane Haddad, Nedjwa Chettibi, 2023) DC electricity output and the absence of moving parts, leading to minor maintenance are the main benefits of the PV/H2 system over other systems. Comparatively, the wind/hydrogen production (wind/H2) system on the other hand is affected by wind's unpredictable nature and needs an AC/DC converter to drive the electrolyser. (Mohamed Nasser, Tamer F. Megahed, Shinichi Ookawara, Hamdy Hassan, 2022) Bilgen in their study showed that using PV tracking system gave the best performance in solar hydrogen production systems but with a greater cost than the traditional PV system. (E. Bilgen, 2001) In this study dynamic agrivoltaics system is also considered as one of the four agrivoltaics configurations for reasons outlined in section 2.2.2.3. Privitera compared in their study the performance of monofacial and bifacial PV modules in hydrogen production. The results showed that the efficiency reached 13.5% for bifacial solar panels instead of 11.55% for monofacial solar panels, corresponding to the increase in hydrogen production to 4.2 g/h/m2 instead of 3.7 g/h/m2 in the case of monofacial panels. (S.M.S. Privitera, M. Muller, W. Zwaygardt, M. Carmo, R.G. Milazzo, P. Zani, M. Leonardi, F. Maita a A. Canino, M. Foti, F. Bizzarri, C. Gerardi, S.A. Lombardo, 2020) Hence and along with the reasons outlined in section 2.2.2.1, bifacial opaque modules have been considered for all agrivoltaics configurations in this study. Detailed parameters of the modules are enlisted in section 3.2 in Table 7.

Shaner in their study compared the costs of hydrogen with and without the electricity grid. Results showed that grid/H2 for hydrogen production is cheaper than using grid/PV/H2 or than using PV/H2. The cost of producing hydrogen were 5.5, 6.1 and 12.5 USD/kg respectively. (Matthew R. Shaner, Harry A. Atwater, Nathan S. Lewis, Eric W. McFarland, 2016) The use of grid as an auxiliary electricity source for the electrolyser is also an important parameter for comparative analysis in this study. Agrivoltaics has comparatively higher CAPEX with respect to ground mounted PV. The extent of impact of an auxiliary grid on the LCOH in such a system needs to be analysed. Hence simulations of different configurations with and without grid have been conducted in this study to compare their economic feasibility for hydrogen production.

The electricity powering the electrolysis unit is the principal parameter from any green energy source to produce hydrogen. The cost of this electricity thus, heavily influences the hydrogen production cost. (Mohamed Benghanem, Adel Mellit, Hamad Almohamadi, Sofiane Haddad, Nedjwa Chettibi, 2023) Figure 11 shows the cost ranges of hydrogen using different green energy sources from studies compiled in the study by Beghanem.

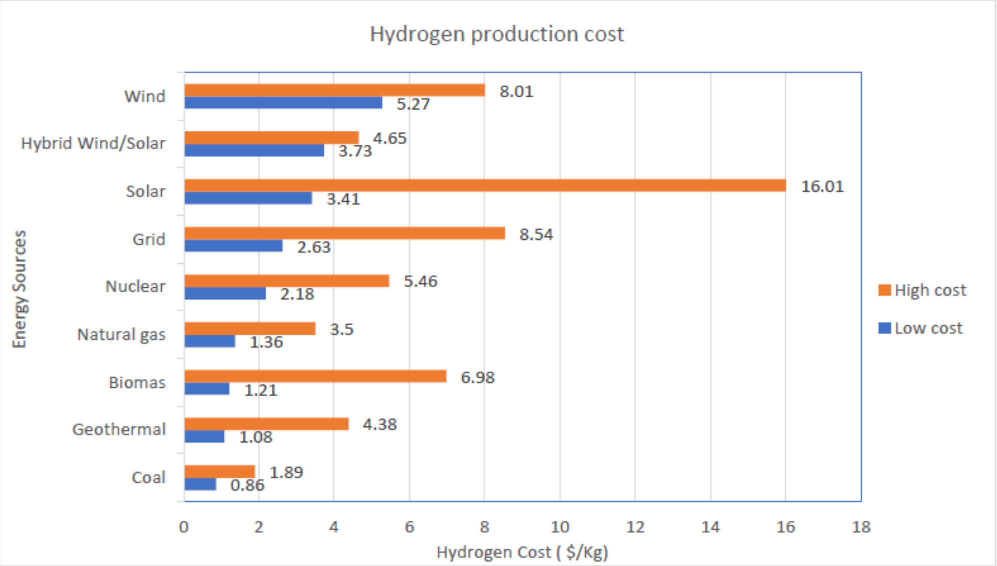


Figure 11: Hydrogen production cost for different energy sources, Source: (Mohamed Benghanem, Adel Mellit, Hamad Almohamadi, Sofiane Haddad, Nedjwa Chettibi, 2023)

Hybrid wind, solar system in both high and low CAPEX scenarios considered in this study seemed to be a cost-effective solution with the two technologies complementing each other. One key goal of this study is to analyse the different scenarios for cost-efficient uniform hydrogen production throughout the year. Hence wind energy like the grid was also considered as an auxiliary source and scenarios with and without wind energy will be simulated to analyse its influence on the results.

2.4 Current status quo of hydrogen in agriculture

Objective 1 of this study is the investigation of current status of use of hydrogen in the domain of agriculture. Harichandan in their study highlighted the impact that green hydrogen could have on Indian agriculture and its Sustainable Development Goals (SDG). Green hydrogen will play a critical role in fulfilling SDG 1 (No Poverty) and SDG 7 (Affordable and Clean Energy) commitments for small-scale farmers. (Sidhartha Harichandan, Sanjay Kumar Kar, Prashant Kumar Rai, 2023) Agrivoltaics will also generate new additional income sources for farmers and rural communities and increase their resilience to climate change risks, helping to achieve the SDG 1 objective along with green hydrogen. Agrivoltaics just like green hydrogen will help in fulfilling SDG 7 objectives by enabling farmer and rural communities to generate and access non-fossil fuel-based energy sources. Green hydrogen can be used to power irrigation systems, which can help to increase crop yields and improve the efficiency of water usage which helps in achieving the SDG 6 objectives (Clean Water and Sanitation). (Sidhartha Harichandan, Sanjay Kumar Kar, Prashant Kumar Rai, 2023) The combination of green hydrogen and agrivoltaics can also be used to power crop drying systems, food processing and storage facilities which can help to improve the quality of crops, improve the shelf-life of food products and reduce food waste. Furthermore, green hydrogen can also be used in powering tractors and crop cutters, promoting SDG 8

(Decent Work and Economic Growth). (Sidhartha Harichandan, Sanjay Kumar Kar, Prashant Kumar Rai, 2023). This objective is defined to see if these impacts have been realized. Different use cases in agriculture to manipulate the demand profile of the produced hydrogen not only helps in achieving these objectives but also helps to reduce the high costs of hydrogen storage, thus reducing the cost of the produced hydrogen and making it cost-effective for all different users. Literature review was conducted to analyse the different use cases for green hydrogen in agriculture and this section presents the results.

Use of green hydrogen to power the agriculture machinery like tractors is an area in which lot of studies were found. That seems to be a straightforward integration point for green hydrogen in the field of agriculture. There have also been efforts to electrify the fleet of agricultural machinery just like the case with passenger vehicles. European Agricultural Machinery Industry Association (CEMA) in their study analysed the electrification of tractors by comparing the performance with respect to an average diesel engine tractor. They considered that traditional system with diesel engine requires a 400l energy reserve of fuel. They considered 9.8 kWh/l to establish equivalence with a full electric variant. This results in a total of 3920 kWh or 1670 kWh due to the 40-45% engine efficiency. Battery pack of 2000 kWh with an energy density of 0.2 to 0.25 kWh/kg would weigh 9-10 tonnes and would takes 5000 l in volume to do the same 8 hours of work as a conventional tractor. Larger tractors would thus exceed acceptable weight limits and subsequently create highly negative, non-sustainable soil compaction. Hence, energy density and weight were highlighted to be the main challenges in full electrification of the tractor fleet. (CEMA - European Agricultural Machinery Industry Association, 2022) Gao and Xue carried out an economic assessment of electric transformation of existing tractors. They had a similar result showing that the cost of transforming electric tractors increases significantly with increasing power, but the transformation is limited by the weight and volume of the battery pack chosen, as well as the driving time. (Huisong Gao, 2020)

Janke in their study have investigated if on-site H2 production could be a feasible alternative to conventional diesel farming from a wind/H2 system located on the island of Gotland, Sweden. Their objective was to find optimal plant configurations that minimized the levelized cost of H2 (LCOH) for the following cases: 1) single-farm H2 production for fuel cell agricultural machinery (FCAM); 2) shared infrastructure between two farms for FCAM and fuel cell minivan (FCMV); and 3) increased scale production by sharing amongst four farms. Delivery vans as additional H2 use-case in each farm, decreased production costs by 35% due to the higher production scale and more distributed demand. They concluded that purchasing diesel is cheaper than on-farm H2 production, for all PtH2 cases and technological scenarios considered. They highlighted that there are however significant differences in purchase costs and tank-to-wheel efficiency between FCAM and conventional diesel agricultural machinery. Thus, further analysis is required to understand the competitiveness of small-scale H2 production for farming activities. (Leandro Janke, Shane McDonagh, Sören Weinrich, Daniel Nilsson, 2020) Carroquino conducted a study in a vineyard, located in the northeast of Spain where surplus energy is used for the on-site production of hydrogen. The hydrogen refuels a hybrid fuel cell electric vehicle, used for the mobility of workers in the vineyard. A diesel agriculture vehicle has been replaced by a fuel cell hybrid electric vehicle (FCHEV), avoiding the consumption of 1084 litres diesel. This fuel savings has prevented the emission of 2732 kg CO2 according to the emission rates of stationary diesel. (Javier Carroquino, José-Luis Bernal-Agustín, Rodolfo Dufo-López, 2019). H2Agrar is a project in Niedersachsen in Germany, which focuses on reducing greenhouse gas emissions from the fuel used by agricultural machinery and transport vehicles. Fendt, a tractor manufacturer in Germany is developing hydrogen-powered prototype tractors for this project. These are to be used under real conditions on two agricultural test farms and the goal is to determine the necessary hydrogen consumption for the tractors and to define the requirements for building a suitable infrastructure.(*H2Agrar -Entwicklung einer grünen Wasserstoff-mobilität für das Agrarland Niedersachsen)* Previously, Fendt presented a tractor in the 200 horse power (hp) class that was equipped with a fuel cell. The hydrogen is supplied via pressure tanks that are housed on the roof and can store around 15 kg of hydrogen, which corresponds to around 80 litres of diesel fuel. (C.A.R.M.E.N. E.V., 2023) Tractor manufacturers New Holland launched world's first hydrogen powered tractor. (New Holland, 2022) It runs on a combination of hydrogen and diesel. The hydrogen is stored in 5 cylinders with 11.5 kg of hydrogen each, which are placed above the tractor cab. Engine manufacturer of agricultural machinery, Deutz launched its first hydrogen engine (TCG 7.8 H2) at the end of 2023. The hydrogen engine uses gaseous hydrogen as fuel and works on the same principle as a petrol engine. (DEUTZ, 2023) Another engine manufacturer Liebherr has also presented their first 6-cylinder hydrogen engine prototype (H966). Series production is expected to begin by 2025 at the latest. (Helmut Süß, 2023) Hence, it can be concluded that use of hydrogen in agriculture machinery especially tractors is already being developed by the industry and soon ready to be an established use case for green hydrogen.

Oxygen is also a by-product of the electrolysis process along-with hydrogen. There is not a developed market and infrastructure for the usage and supply of this oxygen as is the case with hydrogen. There have been lot of studies exploring the use of oxygen particularly in the domain of aquaculture. One of the critical parameters to ensure animal health and survivability is the concentration of dissolved oxygen. The oxygen generated by electrolysis could partially compensate aeration costs, reduce energy demand, and raise production yield. (Alessandra Maganza, Alice Gabetti, Paolo Pastorino, Anna Zanoli, Benedetto Sicuro, 2023) In the previously mentioned study by Janke they also considered an on-site use of O2 where it was considered that all assessed farm configurations are combined with a tank for rainbow trout (freshwater fish species) cultivation where O2 is injected for controlling the dissolved oxygen levels in the water. Produced O2 from the electrolyser was able to offset 23–27% of the total oxygen demand for fish farming. On average, a reduction by 12% on the LCOH was possible by recovering O2, while recovery of waste heat at 60°C in a greenhouse for growing tomatoes was able to reduce the production costs by approximately 5%. This is mostly explained by the large quantities of O2 generated by the water electrolysis process, i.e., 88% of H2O mass becomes O2. (Leandro Janke, Shane McDonagh, Sören Weinrich, Daniel Nilsson, 2020) In southwest Spain, the AQUASEF project applied the idea of self-generated oxygen from renewable energy sources (wind turbines, photovoltaic panels) on aquaculture farms. Pure oxygen produced by electrolysers is used for enhancing aeration in some key stages of the breeding process resulting in an 80% reduction in oxygen consumption. Stored hydrogen is recycled for backup power generation by the fuel cell system. (ARIEMA Energía y Medioambiente SL, 2017). The use of hydrogen has been investigated and applied on a shrimp farm at Mekong Delta in Vietnam in a study by Nguyen. They compared off grid and on grid system configurations to produce onsite pure oxygen according to the changes of dissolved oxygen level in shrimp ponds. They concluded that the advanced aeration system, which uses the electrolyser powered by renewable energy with the support of national grid, is the best configuration in regards to life cycle costs and revenue generated. (Nhut Tien Nguyen, Ryuji Matsuhashi, 2019) Osman in their study discussed the potential synergies of vertical farming and wind, solar and hydrogen fuels. Green oxygen generated during the electrolysis of water could potentially be supplied to the plant roots via the circulating nutrient solution. Supersaturating the nutrient solution with pure oxygen rather than air doubles the yield of hydroponically grown crops and additionally inhibits fungal growth on roots. (Ahmed I. Osman, David Redpath, Eric Lichtfouse, David W. Rooney, 2023) The use of the by-product oxygen from the hydrogen generation process for aquaculture or in manufacturing industries needs to be further explored at a pilot scale. Not only will it be a use case for the produced hydrogen but also help in reducing the cost of the produced hydrogen.

Ammonia which is primarily used to make agriculture fertilizers is made using hydrogen and nitrogen from the air. Indo-German Energy Forum(igef) published a study done by Deloitte analysing the commercial feasibility of a green ammonia production plant in India. India currently consumes ~18.3 million tons of ammonia across industries, such as fertilizer, mining, pharmaceuticals, chemicals, refrigeration and textile. Fertilizer is the largest consumer with more than 90% share, as it is the main input for providing nitrogen in all nitrogenous fertilizers used in agriculture. 1 ton ammonia would require ~180 kg of hydrogen, and this hydrogen would be predominantly green hydrogen going forward. Green ammonia production hence has been identified as one of the first applications of green hydrogen to become commercially viable in India. (Deloitte, 2023) This use-case can be expanded to agriculture around the world but green ammonia in general would be an important application for green hydrogen in all the above-mentioned industries.

Hence, the most studied use cases for green hydrogen in agriculture were found to be:

- Clean and sustainable source of energy for agricultural activities and machinery
- Use of the by-product oxygen in fish breeding
- Use of green ammonia as fertilizer

The agro-livestock sector generates nearly one-third of global anthropogenic GHG emissions or emissions caused by human activity. (Alessandra Maganza, Alice Gabetti, Paolo Pastorino, Anna Zanoli, Benedetto Sicuro, 2023) Promising use cases for the use of green hydrogen in agriculture to mitigate this exist, but the produced hydrogen needs to be easily accessible and cost effective for the farmers to use it. Locally produced hydrogen in the community would make it easily accessible to the farmers which is considered in this study. Agrivoltaics has been considered as the primary source of hydrogen production and its cost-effectiveness has been explored in the next sections as part of objective 2 of this study.

3 Methodology and simulation overview

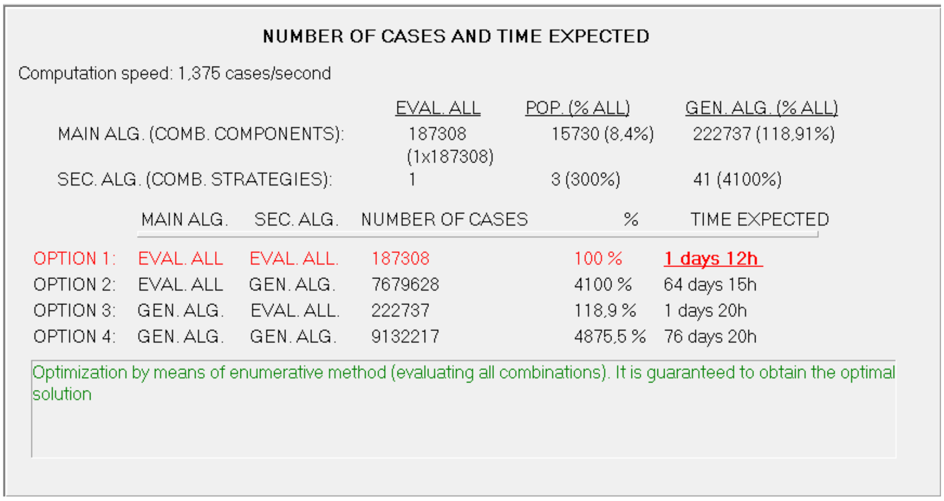
This section describes the simulation methodology followed to set up the simulations as well by the software to optimize the input variables and parameters to generate the results.

3.1 Overview of simulation methodology

Objective 2 of this study is the optimization of system design to minimize the levelized cost of hydrogen (LCOH) using the software MHOGA PRO+. Sub objectives within that are to simulate and analyze three different configurations of hydrogen produced (i.e – grid hydrogen, green hydrogen with auxiliary grid to sell excess electricity generated, off-grid green hydrogen) with four different agrivoltaic system types for cost-efficient uniform hydrogen production. Sensitivity analysis for future cost projection of hydrogen for the years 2040 and 2050 will be conducted for the most optimum scenario/s. MHOGA will simulate combinations with agrivoltaics, wind energy, battery storage and the electricity grid. Twelve simulations as enlisted in section 1.2 with different combinations will be run to find twelve solutions with the lowest LCOH. These different optimum combinations would then be analysed with respect to producing uniform and cost-efficient hydrogen. This section describes in brief the simulation methodology followed within this study and within the software to fulfil this objective.

The Hybrid Optimization Model for Electric Renewables (HOMER) is most widely used and user-friendly software for system design and simulation. (Sunanda Sinha, 2014) Al falahi in their study compiled studies for designing hybrid renewable energy systems worldwide and Homer is observed to be the most widely used software. (Monaaf D.A. Al-falahi, S.D.G. Jayasinghe, H. Enshaei, 2017) It is developed by UL Solutions and it is suitable for carrying out quick prefeasibility, optimization and sensitivity analysis in several possible system configurations. HOMER though allows only single objective function for minimizing the Net Present Cost (NPC). (Sunanda Sinha, 2014) It does not have the option of selling hydrogen for external use as it considers use of hydrogen only as an energy storage option. It has two global control strategies (load following and cycle charging) which are predominantly used for systems with significant load consumption. The systems considered in this study will be generating systems with moderate load requirements and producing hydrogen predominantly for external use.

Improved Hybrid Optimization by Genetic Algorithm (iHOGA) formerly known as HOGA (Hybrid Optimization by Genetic Algorithm) is a C++ based hybrid system optimization software tool developed by the University of Zaragoza, Spain. (Dr. Rodolfo Dufo López, 2024b) Unlike HOMER, it can perform multi-objective optimization and analysis for buying and selling of electric energy when the hybrid system is connected to the utility grid with different cases of net metering and also allows for selling the surplus hydrogen produced by the electrolyser. (Monaaf D.A. Al-falahi, S.D.G. Jayasinghe, H. Enshaei, 2017) iHOGA is for systems in the range of few W up to 5 MW power and MHOGA is for MW power systems, without any limit. (Dr. Rodolfo Dufo López, 2024c) Dufo- Lopez presented a study in which an example hybrid utility-scale grid-connected PV-wind system is located in Zaragoza (Spain) in which the optimization objective was to minimize the levelized cost of hydrogen (LCOH). Four types of scenarios were simulated: type I (islanding), type II (allowed to buy electricity from the grid), type III (not allowed to buy electricity from the grid), and type IV (using grid curtailment and the rest is used to produce hydrogen). (Rodolfo Dufo-López, Juan M. Lujano-Rojas, José L. Bernal-Agustín, 2023). In this study as well, MHOGA will be used to optimize the system design to minimize the levelized cost of hydrogen (LCOH) for four different agrivoltaics system types in India considering different scenarios involving purchasing and selling electricity from the grid. The grid and wind energy will be considered as an auxiliary source along with battery storage to research the framework conditions for green hydrogen production with agrivoltaics. Many different combinations with the selected energy sources are possible and the software would need to simulate all these combinations to find the most optimum with respect to the levelized cost of hydrogen. The user can decide on the main algorithm box on the home page of the software if whether to simulate using genetic algorithm or evaluate all combinations by the enumerative method as shown in Figure 12.



NUMBER OF CASES AND TIME EXPECTED

Computation speed: 1,375 cases/second

	EVAL. ALL	POP. (% ALL)	GEN. ALG. (% ALL)
MAIN ALG. (COMB. COMPONENTS):	187308 (1x187308)	15730 (8,4%)	222737 (118,91%)
SEC. ALG. (COMB. STRATEGIES):	1	3 (300%)	41 (4100%)

	MAIN ALG.	SEC. ALG.	NUMBER OF CASES	%	TIME EXPECTED
OPTION 1:	EVAL. ALL	EVAL. ALL.	187308	100 %	1 days 12h
OPTION 2:	EVAL. ALL	GEN. ALG.	7679628	4100 %	64 days 15h
OPTION 3:	GEN. ALG.	EVAL. ALL.	222737	118,9 %	1 days 20h
OPTION 4:	GEN. ALG.	GEN. ALG.	9132217	4875,5 %	76 days 20h

Optimization by means of enumerative method (evaluating all combinations). It is guaranteed to obtain the optimal solution

Figure 12: Screenshot of main algorithm tab, Source: MHOGA Software

Genetic algorithm is a heuristic technique that does not evaluate all the combinations and can obtain the optimal or a solution near the optimal in low time. (Dr. Rodolfo Dufo López, 2024a) Execution times may increase enormously for simulating with enumerative method for a large number of combinations. (Dr. Rodolfo Dufo López, 2024b) If the time required for simulation is less than the maximum allowed time then the software chooses enumerative method to find the most optimum solution. Genetic algorithm is selected if that is not the case. In our case as time was not a key constraint and the goal was to find the most optimum solution, maximum time for simulation was set so high that enumerative method was always selected as shown in Figure 12. Each combination is then simulated during the system lifetime in steps of 1 hour. MHOGA provides the option to simulate either just for 1 year or multiperiod over the entire system lifetime. Multiperiod was selected for this study to obtain more realistic results. The user can then specify individual values or an annual increase or decrease in electricity or hydrogen prices, the generation of the technologies or resources considered, reduction in the end-of-life battery capacity, load in the system and operation and maintenance for the resources considered. All default values pre-defined in the software were considered for this study. If a particular combination meets the constraints as described below, then it calculates the LCOH, considering all the costs and incomes during the lifetime of the system and converts all of them to the first year taking into account inflation and interest rate. (Dr. Rodolfo Dufo López, 2024a).

When genetic algorithm is used then MHOGA makes use of two genetic algorithms, the main algorithm and the secondary algorithm. The main algorithm provides an optimum configuration for the PV modules, the wind turbines, batteries, and the electrolyser in order to minimize LCOH. The secondary algorithm obtains the most appropriate control strategy for minimizing costs for any given component setup provided by the main algorithm. (for eg: electrolyser would only be run or batteries be charged when the price of electricity from the grid falls below a certain value) All possible solutions provided by genetic algorithm can be looked at as "individuals" within a certain species. Each individual is actually a combination of the variables ("genes") to be optimized. In our case, the variables or "genes" correspond to the hybrid system components (number of PV modules, wind turbines, etc.) and the variables of the control strategy. The first "generation" includes a random set of individuals, which is called "population". These individuals are "crossed" which means they mix with each other. There is higher probability of reproduction for the best individuals, i.e those with the lowest LCOH or "best fitness". New individuals are generated by reproduction ("children"), thus replacing the worst "parents", and creating a new generation. Some individuals "mutate" (values for variables or genes are randomly altered). This process repeats itself, with more and more new generations, and better solutions are provided as the algorithm progresses. Genetic algorithm requires numeric value of system parameter like the number of generations, the population, mutation and crossover (breeding) rates and uniformity in mutation. (Dr. Rodolfo Dufo López, 2024b)

In our case we optimize for minimizing the LCOH. It is calculated as follows:

$$LCOH = \frac{Total\ Present\ Cost_{H2}}{\sum_{y=1}^{Lifetime}\left[\left(\sum_{0}^{8760\ h} H_{2sold}\right)\times\left(1+Inflation_{g}\right)^{y}/\left(\left(1+I\right)^{y}\right)\right]} \tag{1}$$

Formula 1: Formula for calculating LCOH
Source: (Dr. Rodolfo Dufo López, 2024b)

Where $Total\ Present\ Cost_{H2}$ is the sum of the total present costs of the system during its lifetime i.e NPV minus incomes due to selling hydrogen. $Inflation_{g}$ is the general inflation rate and I is the interest rate for year y. H_{2sold} is the amount of hydrogen sold externally.

$$NPV = Incomes_{sellE} + Incomes_{sellH_2} - Cost_{purchE} - Cost_{rep} - Cost_{O\&M} - Cost_{inst} \tag{2}$$

Formula 2: Formula for calculating NPV
Source: (Dr. Rodolfo Dufo López, 2024b)

where $Incomes_{sellE}$ and $Incomes_{sellH_2}$ are respectively the income due to electrical energy sold to the AC grid and hydrogen sold externally. $Cost_{purchE}$ is the electrical energy purchased from the AC grid. $Cost_{rep}$, $Cost_{O\&M}$ and $Cost_{inst}$ are respectively the costs due to replacement, operation and maintenance and installation of individual components. All incomes and costs are normalized to the first year over the system lifetime using interest and inflation rates. MHOGA allows the use of specific inflation rates for specific components in addition to the general inflation rate.

We can set constraints to define the boundary conditions for our solutions and the variables to be considered for optimization. In NPV maximization projects or in this case LCOH minimization projects, where there is typically no/little load i.e grid-connected systems to sell the electricity to the AC grid and hydrogen for external use there can be five constraints for optimization: (Dr. Rodolfo Dufo López, 2024b)

- Maximum investment cost - By default a very high value is set so that this constraint is not considered. Default values were kept in this study.
- Minimum capacity factor - Annual energy sold divided by the peak annual renewable power. By default, it is 0% so that this constraint is not considered. Default values were kept in this study.
- Minimum renewable fraction - By default it is 0% so that this constraint is not considered. It denotes the fraction of annual energy injected to the renewable generators. Default values were kept in this study.
- Maximum unmet load - It is load that cannot be supplied by the system nor by the AC grid. By default, it is 100% so that this constraint is not considered. Maximum and minimum number of components have been set for simulating the combinations as described below in section 3.2. Test simulations with maximum number of components allowed as the selection were simulated to set up the software first as they take hardly any time due to the reduced complexity. It was then observed that change of unmet load from 10% to 0.1% increases the number of batteries used in the system significantly which increases the cost of hydrogen by 13 %. Change from 10% to 5 % on the other hand only increases the costs by 1 %. This observation is also in accordance with results from the literature where it was seen that the last 5–10% of load in a high renewable energy system can often represent a substantial portion of the total system costs. (Will Hall, 2020) Hence, this constraint is set at 5%.
- Maximum land use - By default a very high value is set so that this constraint is not considered. Default values were kept in this study.

MHOGA is suitable to simulate ground mounted PV configurations. Agrivoltaic systems are comparatively installed at a higher elevation. Hence, they cannot be accurately simulated using the MHOGA internal tool to calculate the PV irradiation on the tilted surface. MHOGA though provides the option of importing the generation of a PV generator. Annual generation of a 1 MWp generator can be imported and then MHOGA uses these base values for all the other combinations. Fraunhofer ISE's internal "APyV tool" was used for the light simulation and the electrical yield was estimated from it. This was done for all the four agrivoltaics system types viz., overhead arable farming, overhead permanent crop, interspace vertical and overhead dynamic described previously and the result file was imported for the respective simulations. APyV tool uses the Radiance ray tracing software, which has been validated in many studies by Fraunhofer ISE and was developed in 1985 by Greg Ward at the Lawrence Berkeley National Laboratory (Ward & Shakespeare, 1998). This software uses backwards ray tracing i.e rays of light are traced back to the place of their origin, the light source. Ray tracing means that the software analyses individual light rays in a predefined 3D environment which is chosen by the user. At these locations, which are also called sensor points, the number of light rays that arrive is calculated to estimate the irradiation at that point. Those days are selected for the simulation which represent an average irradiation in the respective month. These irradiation values are used to estimate the electrical yield by considering the performance ratio.

3.2 Setting and validation of optimization variables and parameters

This section describes the optimization parameters and variables used to setup the simulation. Tabular overview of the individual steps taken has been provided in the Annex in Table 21. Figure 13 shows a flowchart of the category headings of the parameters set in the software.

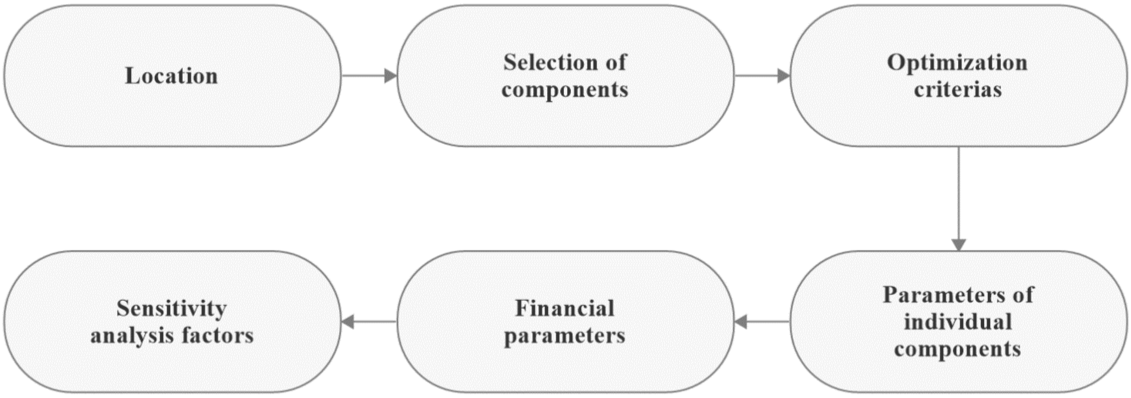


Figure 13: Flowchart of category headings of set parameters; Source: Own creation

3.2.1 Input variables and parameters

The first parameter to choose was the location of the study. The Energy and Resource Institute (TERI) conducted their study on the role of hydrogen in India by considering different clusters in India suitable for green hydrogen generation and application. They determined ten economically significant clusters based on the total production capacity of four industries viz., refineries, caustic soda and fertilizer manufacturing, iron and steel. These ten clusters were then ranked according to their renewable energy potential. Gujarat cluster was ranked at position one. (Will Hall, 2020) UK India Business Council conducted a study in 2023 describing the green hydrogen landscape in India. They ranked twelve states in India on six parameters viz., installed capacity of solar and wind power, freshwater availability, port access and ease of doing business. These parameters had a weightage of 25%, 10%, 30%, 15% and 20% assigned to them respectively. Scores from 1 to 5 were given for each parameter with each value having a pre-defined significance. Tamil Nadu was ranked highest with a score of 3.7 and Madhya Pradesh the lowest with a score of 1.8. Gujarat with a score of 3.6 was ranked second. (Gunjan Sharma, Manish Verma, Mansi Jain, Shivraj Chaudhary, 2023) Just like the PM Kusum scheme described in section 2.1 was launched to enable energy security for farmers in in India the Gujarat government launched the Suryashakti Kisan Yojana/Scheme (SKY). In this scheme specifically for farmers in Gujarat, 60 % subsidy on the cost of the project will be given by the state and central governments, 35% of the project cost will be financed through loan with interest rates of 4.5% to 6% and remaining 5% of the project cost will be borne by the farmer. Farmers can use solar energy to generate electricity for their own captive consumption and sell the excess to the grid. Total duration of the scheme is 25 years which is split between a 7-year period and an 18-year period. Farmers will get per unit tariff of Rs 7 (Rs 3.5 by GUVNL or the state electricity regulation board and additional Rs 3.5 by state govt.) (0.078 Eur/unit according to the conversion rate shown in Table 13) for the first 7 years and Rs 3.5 (0.039 Eur/unit according to the conversion rate shown in Table 13) for succeeding 18 years by distribution companies. 12,400 farmers of 33 Districts in total will be benefitted under this scheme. The state government spends about Rs. 4,500 – 5,000 crore per year (503 Mil Eur/year to 560 Mil Eur/year according to the conversion rate shown in Table 13) as subsidy on electricity for irrigation purpose. This subsidy cost can be brought down by proper implementation of SKY Scheme. (Gujarat Power Research and Development Cell) Hence, this is expected to lead to an increased uptake of agrivoltaics in Gujarat in the upcoming years. Green ammonia in fertilizers as stated in section 2.4 will be an important use case of green hydrogen in the future. The Deloitte study on green ammonia in India stated that demand of ammonia is concentrated in the states of Gujarat, Uttar Pradesh, Maharashtra, Rajasthan, Madhya Pradesh, and Andhra Pradesh due to presence of large fertilizer plants in these states. Similar to the previously stated UKBIC study, these states were ranked in this study from 1 to 5 in eight parameters viz., solar and wind potential, water availability, ammonia terminal availability at port, port access, ammonia demand in 2030, ease of doing business, presence of micro, small and medium enterprises around the cluster to support the ecosystem. The parameters had a weightage of 5%, 5%, 10%,10%, 20%, 35%, 10% and 5% respectively. Gujarat was ranked first with a score of 4.95 and clusters of Rajasthan, Madhya Pradesh were ranked last with a score of 1.85 (Deloitte, 2023). As stated in section 2.3, a hybrid system of agrivoltaics and wind energy will be simulated in this study. Kumar in their study on the overview of advances and development of wind-solar hybrid renewable energy technologies in India provided an overview of wind, solar and hybrid potentials of different states in India. Wind potential for Gujarat at 120 m hub height is 157 GW for and solar potential is 3087 GW. The hybrid potential of these technologies is 2794 GW. (J Charles Rajesh Kumar, MA Majid, 2023) They also provided a list of such hybrid projects commissioned in India with their tariffs which has been later used to determine the electricity tariff considered for this study. Hence Gujarat due to its conducive location, good scores in these studies and policy support was chosen as the location for this study. Gujarat energy regulatory commission issued a list of hybrid wind and solar projects commissioned in Gujarat up to March 2023. The exact location was chosen to be one of the locations from this list as shown in Table 2.

Table 2: Location for the study; Source: Own creation

Latitude	**Longitude**	**Village**	**District**	**State**	**Country**
22°33'47.2"N	70°41'19.5"E	Virvav	Morbi	Gujarat	India

The individual components were selected next. Janke in their previously introduced study on feasibility of a hybrid wind on-site H2 production system considered a scenario where farmers finance H2 production and use by means of leasing land to wind power project developers. Such a business model was considered advantageous for both parties as farmers obtain additional revenues by leasing their land for wind power production and they can locally produce clean fuel to decarbonize their activities. Project developers potentially enhance their wind power production by selling curtailed electricity to farmers and support for the wind farm will likely be much greater with local involvement. (Leandro Janke, Shane McDonagh, Sören Weinrich, Daniel Nilsson, 2020) In this study as well H2 production with centralized agrivoltaics systems divided amongst multiple farmers has been considered. In the previously introduced study done by The Energy and Resource Institute in India (TERI) on the role of hydrogen in India, their simulated model never finds it optimal to build battery capacity to smooth electricity supply, even though battery costs in the model drop by more than half between 2020 and 2050. This is largely since the conversion loss of power to hydrogen production must be incurred anyway, and thus, hydrogen storage represents a more efficient round-trip process than battery storage of electrical energy. (Will Hall, 2020) Mallapragada in their study assessed the cost and conditions of continuous H2 supply via PV-electrolysis coupled with energy storage. They found that battery storage was very rarely a component in the optimal system design at any of the ten locations considered. The availability of low-cost H2 storage makes it cost effective to use more of the PV electricity supply by oversizing whenever it is available and store the produced H2 for providing supply at other times. (Dharik Sanchan Mallapragada, Emre Gencer, Patrick Insinger, David William Keith, Francis Martin O’Sullivan, 2020) Regardless in this study battery storage is considered in the components to analyse its utilization by the software in the optimum system. Thus, components chosen in this study are – agrivoltaics generators, wind turbine generators, electrolysers with compressed pressure vessel storage, lithium-ion battery storage and electricity grid.

Next the user must select the optimization criterions. As described in section 1.2, optimization objective for this study is the minimization of the levelized cost of hydrogen. The user must set a constraint here of minimum hydrogen to be produced annually. India conducted its first auction for green hydrogen and electrolyser subsidies in 2024. (Polly Martin, 2024) Average commissioned capacity of hydrogen was approx. 48000 tonnes/year and the lowest was 2000 tonnes/year. Hence this constraint of minimum hydrogen to be produced annually for this study is set at 2000 tonnes/year. Specific energy consumption of the electrolyser is assumed to be 52 kWh/kg as stated in Table 9. (Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023) Hence approx. 12 MW installed capacity is needed to fulfil this annual demand of the electrolyser. In addition to this demand, we also consider a load demand of approx. 100 MWh/day. This system is located in Morbi district in Gujarat as stated previously. Misra in their study developed a suitable hybrid energy system (HES) for the electrification of a cluster of five villages located in the Kutch district of Gujarat. Area's load demand was found out to be 1,548 kWh/day which rudimentarily accounts for 310 kWh/day for each village. Exact load data of all the villages in Morbi district could not be readily obtained. Hence 310 kWh/day/village was considered as the average demand and the demand for all villages in Morbi district was estimated accordingly. There are 349 villages in this district. (National Informatics Centre, Government of India, 2024) Thus, load demand of approx. 108 MWh/day was estimated for this study. MHOGA allows users to define a load profile by importing it externally or generating one using exact values or monthly averages. It also has predefined load profiles of 100 MWh/day for residential or town localities. The town load profile was a close representation of a load profile for this study. Hence it was directly used with all default values for the required parameters. This 100 MWh/day load demand requires approximately a generation capacity of 4 MW considering full load operating hours of 8760. Hence, minimum generation of approximately 16 MW is needed to meet the demand from the load and the electrolyser. This though does not consider the availability of the wind or solar resources at different times of the year and its interplay with the load and electrolyser demand. Hence, the system needs to be oversized. 300 % oversizing of the generators has been considered to specify the maximum and minimum number of components as shown in Table 3. The rational for 300% as the exact setting is a trial-and-error method where in test simulations similar to the ones simulated to select the constraint of unmet load were performed with 30%, 60% and 100% oversizing for off grid configuration. The results did not meet the minimum constraint of 2000 tonnes of hydrogen per year. Oversizing of 200% was observed to increase the LCOH by 10 % due to increase in the battery capacity and 250 % oversizing increased the LCOH by 4 % but it reduced the electrolyser capacity selected thus producing less hydrogen. Hence 300 % was selected. Minimum number of generators is set to 0 to consider the possibility of not having any wind or PV generators in the system. Maximum and minimum number of generators set are shown in Table 3. Maximum number of batteries has been set to 10 considering maximum energy storage capacity required of 84 MWh. This was calculated according the specifications from the handbook of battery storage considering standard 4 hour storage, battery efficiency of 95% and depth of discharge of 80%. (Asian Development Bank, 2018)

Table 3: Minimum and maximum number of components; Source: Own creation

Component	**Minimum number of units**	**Maximum number of units**
PV	0	128
Wind	0	32
Batteries	0	10

66 kV was set as the AC voltage as that was the most used for the hybrid project commissioned in Gujarat mentioned previously. 66 kV line voltage is also commonly used for sub-transmission of large power levels in distribution over middle distances. (Edvard Csanyi, 2017)

The parameters of the individual components were selected next. Versions 1.1, 2.1, 3.1 and 4.1 as depicted in section 1.2 include the option of purchasing and selling power to/from the grid. Versions 1.2, 2.2, 3,2 and 4.2 include the option of only selling power to the grid. MHOGA allows user to individually select these configurations. In the Load/AC Grid tab, the user must set the price and tariff of purchasing and selling to the grid, the emissions to be considered for the analysis, the selling price of the hydrogen generated and the inflation to be set for the prices considered which can be different to the general inflation considered in the overall simulation. Corresponding values used for this study are depicted in Table 4. MHOGA also allows user to set a limit on the power imported or sold to the grid, import hourly or tariff values for specific periods. Fixed values have been considered in this study as shown in Table 4. Electricity purchase and sell prices were calculated as average prices from prices considered in the sources enlisted in Table 22 and Table 23 in the Annex. The user can specify a value for random generation of non-availability of AC grid which was set at 2 % in this study. User can decide between AC grid and storage/generator to prioritize supplying the energy not covered by renewables. It was set for storage/generator in this study. Hydrogen selling price data is not available for India. Hence, the selling price was calculated considering the average production price of hydrogen currently in India from different sources of Rs 419/kg (4.69 Eur/kg according to the conversion rate shown in Table 13) and a net profit margin of 9.55% for the energy sector as of Q1 2024 (CSIMarket, 2024). Ministry of Statistics and Programme Implementation of Government of India provided monthly inflation rates for fuel and light from January 2014 to April 2024. Annual inflation was calculated as an average value from these values.

Table 4: Load/AC Grid tab parameters; Source: Own creation

Parameter	**Unit**	**Value**	**Sources**
Fixed buy price	€/kWh	0.077	(Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023) (Takuma Otaki, 2023) (Will Hall, 2020)
Fixed sell price	€/kWh	0.030	(J Charles Rajesh Kumar, MA Majid, 2023)
Hydrogen sell price	€/kg	5.13	((CSIMarket, 2024), (Dezan Shira & Associates, 2023), (Sonal Gupta, Rupesh Kumar, Amit Kumar, 2024), (Hafiz Muhammad Uzair Ayub, Sabla Y. Alnouri, Mirko Stijepovic, Vladimir Stijepovic, Ibnelwaleed A. Hussein, 2024))
Annual inflation	%	5.13	(Ministry of Statistics and Programme Implementation, 2024b)
Emmision	$kgCO_2/kWh$	0.700	(Will Hall, 2020)

As described in section 3.1, the generation profiles of the PV generators were imported to accurately represent the generation profile of the different agrivoltaic systems considered. Dynamic system can be simulated using the internal tracking algorithm of the software along with the irradiation profile of overhead static arable farm system placed horizontally. The software will then simulate the horizontal axis tracking to estimate the generation. Wide discrepancy was observed in the results as compared to the simulation from the internal Fraunhofer ISE tool described previously. Hence, it was decided to use the same methodology for the overhead dynamic system as used for the other agrivoltaic systems considered. Jinko solar Tiger Pro 545Watt bifacial modules have been selected for simulating the generation profiles. (Jinko Solar, 2024) Dhingra in their study on investigating the optimal tilt of photovoltaic solar panels in Ahmedabad city of Gujarat, India concluded that the optimum tilt angle was 19.179° at a latitude of 23.09°. (Rajveer S Dhingra, Varyam Gupta, 2021) Hence, tilt angle of 20° was selected for this study. System parameters and costs are based on commissioned agrivoltaics projects in India. This information was gathered from project developer in India. System parameters are enlisted in Table 5.

Table 5: Agrivoltaic system parameters; Source: Own creation

Parameter		**Unit**	**Value**	**Sources**
Module tilt		°	20	(Rajveer S Dhingra, Varyam Gupta, 2021)
Clear height	Overhead arable farm	m	3	Commissioned projects in India
	Overhead permanent crops	m	3	
	Interspace vertical	m	1.5	
	Overhead dynamic	m	3	
Pitch distance	Overhead arable farm	m	8.5	
	Overhead permanent crops	m	7	
	Interspace vertical	m	10	
	Overhead dynamic	m	7	

In the wind resource tab, the user must download the wind speed and temperature data to enable the software to estimation the generation of the wind turbine. We can also import the generation profile directly as in the case of the solar resource or import the wind speed data from an external source. Renewable Ninja data was directly available in the software to download at any wind turbine height. Ministry of New and Renewable Energy of Government of India prepared a wind resource map at 120 meter height, as most of turbine hub heights being installed are more than 100 meters. (Press Information Bureau, 2017) Hence 120 m was chosen as the height here and the data was downloaded from Renewable Ninja.

Next step is setting the parameters of the wind turbine in the components – Wind tab. They have been listed in Table 6. A standard wind turbine of 2MW was selected from the database of the software and some of the parameters were modified as shown below. The number of such components to be used will be determined by the software in the results. The CAPEX of the wind turbine has been calculated as average price from prices considered in the sources enlisted in Table 6. Detailed tabular overview of the prices from the sources is provided in the Annex in Table 26.

Table 6: Components Wind tab parameters; Source: Own creation

Parameter	**Unit**	**Value**	**Sources**
Height above sea level	m	90	(LAT LONG DATA)
CAPEX	M€	1.8	(Central Electricity Authority, 2023), (Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023), (Raj Sawhney, John Hearn, Ross Hibbett, Khaya Kingston, Makenna Parkinson, Joseph Majkut, 2023)
Replacement cost	M€	1.5	Calculated with default scaling factor from the software
Height	m	120	Same as height set before

Consistently, parameters in the components – solar tab have been enlisted in Table 7 and detailed tabular overview of the prices from the sources is provided in the Annex in Table 25. PV generators of 1 MWp were selected for optimization considering the average installed capacity for agrivoltaics per farm around the world and in India. CAPEX has been obtained from commissioned projects in India as stated previously. Table 7 shows the parameters of the PV generators used for simulating the overhead static arable farming agrivoltaic system configuration. The modified parameters have been enlisted below.

Table 7: Components PV tab parameters; Source: Own creation

Parameter	**Unit**	**Value**	**Sources**
PV Generator overhead static arable farming - 1 MWp			
Power	MWp	1	
CAPEX	M€	0.56	Data from commissioned projects in India
O&M	%/yr	2	(Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023)
NOCT	°C	45	(Jinko Solar, 2024)
Power T coef	%/°C	-0.35	(Jinko Solar, 2024)

Similarly, CAPEX for 1 MW generators used to simulate the other agrivoltaics systems have been enlisted in Table 8. Agrivoltaics guidelines by Fraunhofer ISE provide the comparison in costs of the different agrivoltaics system configurations. (Fraunhofer ISE, 2024) These scaling factors have been used to estimate the cost of the different system configurations in an Indian context. Rest of the parameters remain the same as enlisted above.

Table 8: Agrivoltaic system CAPEX scaling factors; Source: Own creation

Parameter	Unit	Value	Scaling factor
Overhead arable farm	M€	0.56	1
Overhead permanent crops	M€	0.48	0.86
Interspace vertical	M€	0.39	0.70
Overhead dynamic	M€	0.71	1.26

Parameters for the electrolysers considered need to be set in the components – fuel cell/electrolyser tab. Electrolyser used in this study was modelled based on the electrolyser used in the Fraunhofer country analysis study for Power-to-X referenced previously. Parameters for this PEM electrolyser have been provided in Table 9. Parameters used for the simulation have been enlisted in Table 10.

Table 9: Electrolyser properties; Source: Own creation

Parameter	Unit	Value
Lifetime	years	30
Stack lifetime	hours	85000
H2 production rate	tonnes/h	19.3
SEC at rated production	kWh/kg	52
Specific power consumption	kWh/kg	0.4
Total rated mass flow for compression	tonnes/h	19.3

Like PV and wind generators, CAPEX has been considered to be average of the different prices considered from the sources and detailed tabular overview of the prices from the sources is provided in the Annex in Table 27. The costs of the tank which will store the H2 before selling it, plus the cost of compressor, rectifier etc. must be included in the electrolyser costs. (Dr. Rodolfo Dufo López, 2024a) Electrolysers of capacities 25 MW, 30 MW, 35 MW, 40 MW have been chosen for this study. 25 MW is chosen to meet the minimum constraint of 2000 tonnes of hydrogen per year based on the properties of the electrolyser considered. Steps of 5 MW are chosen to observe the impact on LCOH based on electrolyser capacity. H2 pressure vessel storage for one week of hydrogen capacity has been considered for the on-grid variants. MHOGA allows in the control strategy to run the electrolyser at full load which means the electrolyser runs at full load, using the renewable power and, if not enough, buying electricity from the grid if that is allowed.(Dr. Rodolfo Dufo López, 2024b) The electrolyser on the other hand does not run at full load in the off-grid variants. Uniform supply of hydrogen to the industries is very important considering the high penalties on failure to meet the demand in a timely manner. Hence, storage capacity of one month is chosen for these variants. It can also be designed to run at full load by increasing the % of oversizing and/or increasing the battery storage capacity. This increases the costs of producing hydrogen considerably compared to the increase in costs of the higher storage capacity which has also been analysed and discussed in section 4.

Table 10: Components Electrolyser tab parameters; Source: Own creation

Parameter		**Unit**	**Value**	**Sources**
H2 mass flow limit		% of rated	5	(Rodolfo Dufo-López, Juan M. Lujano-Rojas, José L. Bernal-Agustín, 2023)
Factor efficiency			0.45	(Rodolfo Dufo-López, Juan M. Lujano-Rojas, José L. Bernal-Agustín, 2023)
CAPEX Storage		Mil Eur/MW	0.014	Calculated using prices provided in (Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023)
CAPEX Compression		Mil Eur/MW	0.025	Calculated using prices provided in (Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023) (Miao Yang, Ralf Hunger, Stefano Berrettoni, Bernd Sprecher, Baodong Wang, 2023)
Acquisition Cost – On grid systems	25 MW	Mil Eur	17.64	(Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023) (Will Hall, 2020) (Takuma Otaki, 2023) (IRENA - International Renewable Energy Agency, 2023)
	30 MW	Mil Eur	21.17	
	35 MW	Mil Eur	24.70	
	40 MW	Mil Eur	28.23	
O&M – on grid systems	25 MW	Eur/yr	352893.9	2% of CAPEX; (Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023)
	30 MW	Eur/yr	423472.7	
	35 MW	Eur/yr	494051.5	
	40 MW	Eur/yr	564630.3	

Acquisition Cost – Off grid systems	25 MW	Mil Eur	18.20	(Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023) (Will Hall, 2020) (Takuma Otaki, 2023) (IRENA - International Renewable Energy Agency, 2023)
	30 MW	Mil Eur	21.84	
	35 MW	Mil Eur	25.48	
	40 MW	Mil Eur	29.12	
O&M – off grid systems	25 MW	Eur/yr	364060.6	2% of CAPEX; (Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023)
	30 MW	Eur/yr	436872.7	
	35 MW	Eur/yr	509684.8	
	40 MW	Eur/yr	582496.9	

Battery and inverter parameters were set up next in the respective tabs. Default lithium-ion battery of 10 MWh and inverter of 1 MW was selected. Cost parameters were modified for both selections as shown in Table 11. CAPEX has been considered to be average of the different prices considered from the sources and detailed tabular overview of the prices from the sources is provided in the Annex in Table 28.

Table 11: Components Battery and Inverter parameters; Source: Own creation

CAPEX	**Unit**	**Value**
Battery	Mil Eur/ 10 MWh	1.39
Inverter	Mil Eur/MW	0.042

Parameters used in the financial data tab were set next and they have been enlisted in Table 12. Indian Renewable Energy Development Agency Limited (IREDA) is a Government of India Enterprise under the administrative control of Ministry of New and Renewable Energy (MNRE). It is engaged in promoting, developing, and extending financial assistance for setting up projects relating to new and renewable sources of energy and energy efficiency/conservation. The financing conditions of IREDA have been considered as the framework financing conditions for this study. (Indian Renewable Energy Development Agency Limited [IREDA], 2024) Installation cost and variable initial cost needs to be set by the user in %. Default value of 30 % was changed to 10 % as the CAPEX considered before for all technologies except wind generators involves this cost. Similar to the previously calculated inflation for Fuel and Power, the general inflation was calculated. Ministry of Statistics and Programme Implementation of Government of India provided monthly inflation rates from May 2023 to April 2024. Annual inflation was calculated as an average value from these values. (Ministry of Statistics and

Programme Implementation, 2024a) Nominal discount rate was set at 6.5% by the Reserve Bank of India in April 2024. (Reserve Bank of India, 2024).

Table 12: Financial data tab parameters; Source: Own creation

Parameter	**Unit**	**Value**
Amount of loan	%	70
Installation cost and variable initial cost	%	10
Duration of loan	years	15
Interest rate	%	10.5
Nominal discount rate	%	6.5
Inflation	%	5.37

MHOGA considers the load as one single component. The revenue generated from selling the electricity is calculated at the point of connection to the grid. Hence, the revenue from selling electricity to the loads of the 349 villages in the considered district is not considered by the software directly in the NPV calculations. Control strategy selected for the simulations ensures that the electricity generated is used to meet the load demand and excess demand or generation is then sold or purchased to the grid. Hence, this revenue from selling electricity to fulfill the load demand of the villages has been considered in the extra cash flow option in the financial data tab. Paschim Gujarat Vij Company Limited – state electricity distribution company for the considered region has specified electricity tariffs based on the units consumed. Average tariff of Rs 1.318 per kWh (0.015 Eur/unit according to the conversion rate shown in Table 13) has been considered. This also includes the Rs 1 per kWh green tariff as specified to meet the energy demand by green energy. Detailed tabular overview of the prices from the sources is provided in the Annex in Table 29. Load met needed to be calculated to input this revenue here. Considering load in the system of 102 MWh/day and unmet load of 5 % as set before, annual revenue was calculated to be 0.51 Mil Eur. This was considered over the system lifetime by considering the inflation rate of 5.13 % as set before.

Euros is the currency used for the study. All parameters have been converted to Euros using the exchange rate shown in Table 13 as of 25.04.2024. (Reserve Bank of India) (European Central Bank)

Table 13: Currency conversion rates; Source: (Reserve Bank of India) (European Central Bank)

Rs	**EUR**	**USD**	**EUR**
1	0.0112	1	0.9358

Parameters for the sensitivity analysis were set next in the sensitivity analysis tab. MHOGA allows users to perform sensitivity analysis for wind speed, global irradiation, load, interest rate, inflation rate and acquisition cost. MHOGA also has the option to perform probability analysis to analyze variability of the average value of load, irradiation, wind speed and fuel price inflation. Different combinations can then be simultaneously analyzed to see the correlation between them. Probability analysis has not been conducted in this study. Sensitivity for acquisition cost for future cost projections for 2040 and 2050 were performed in this study. Acquisition cost until 2050 were obtained from different sources provided in the Annex in Table 30 and Table 31. Curves and logarithmic equations were plotted using these values to obtain scaling factors for the acquisition cost. They have been enlisted in Table 14 and the specific equations used can be seen in the Annex in Table 32, Figure 27, Figure 28, Figure 29 and Figure 30.

Table 14: Sensitivity analysis tab parameters; Source: Own creation

Year	**Scaling Factor**			
	Solar	**Wind**	**Electrolyser**	**Battery**
2024	1	1	1	1
2040	0.74	0.93	0.79	0.47
2050	0.59	0.90	0.71	0.31

3.2.2 Validation of optimization variables and parameters

Simulations performed initially highlighted two bugs in the software. The parameter 'Export' in Table 15 depicts energy that can be exported to the grid. This was observed to be arithmetically not adding up after considering the energy generated by the generators and the load demand as can be seen in Table 15. The problem was identified in the internal calculation methodology of the software specifically in regard to the setting of the option – 'priority to supply energy not covered by renewables'.

Table 15: Export error observed in the initial simulations; Source: Own creation

Date	**Hour**	**Load (MW)**	**AC_load (MW)**	**PV(MW)**	**Wind (MW)**	**Electrolyser (MW)**	**Export (MW)**
01-January	14:00	2,63	2,61	22,77	0	25	-7,61
02-January	16:00	1,05	1,04	14,72	2,91	25	-11,19

01-January	14:00	2,63	2,61	5,01	0	25	-25,37
02-January	16:00	1,05	1,04	3,24	0,61	25	-24,98

The second bug was observed after the extra cash flow from the load demand of the villages considered was set in the ‘extra cash flow’ tab. The results specifically NPV and LCOH after finishing the simulation were observed to be changing two or three times with every click in the result table. The problem was identified to be in the ‘extra cash flow’ tab. The software automatically set the cash flow for the 25th year of simulation to zero and recalculated that part with every click.

Both bugs have since been acknowledged and fixed by the developers of the software.

4 Results and Discussion of all system configurations

Objective 2 of this study is the optimization of system design to minimize the levelized cost of hydrogen (LCOH) using the software MHOGA PRO+. Objective 2.1 is to simulate and analyze three different types of hydrogen produced – grid hydrogen, green hydrogen with auxiliary grid to sell excess electricity generated, off-grid green hydrogen. Objective 2.2 is to analyze the feasibility of the four different agrivoltaic system types for cost-efficient uniform hydrogen production. Objective 2.3 is to conduct sensitivity analysis for future cost projection of hydrogen for the years 2040 and 2050. Objective 2.1 and 2.2 have been defined separately for clarity for understanding. Results though have been analyzed all together from the perspective of the feasibility of configuration of hydrogen produced, suitable agrivoltaics system type and future cost projection in this section.

4.1 Analysis for all hydrogen system configurations

Table 16 shows the results obtained in respect to the type of hydrogen produced. These are the results for the base case of 2024. Minimization of LCOH was selected as the optimization criteria as explained previously. Results in this table have also been classified accordingly. Green + grid to sell interspace vertical configuration has the lowest LCOH in green followed by the other system types and green – off grid system configuration. Grid configurations have the highest LCOH in red with overhead dynamic system type having the highest LCOH. Reasons for the same have been analysed below.

Table 16: Results obtained in respect to the type of system configuration; Source: Own creation

Version	**Type of hydrogen**	**Type of agrivoltaics**	**Results**	
			LCOH	**NPV**
			€/kg	**M€**
1.1	Grid	Overhead static -arable farming	4.71	-61.10
2.1		Overhead static - permanent crops	5.37	-14.23
3.1		Interspace vertical	5.28	-5.42
4.1		Overhead dynamic	5.42	-20.24
1.2	Green + grid to sell	Overhead static -arable farming	3.81	85.49
2.2		Overhead static - permanent crops	3.78	87.93
3.2		Interspace vertical	3.67	96.99
4.2		Overhead dynamic	3.92	81.51
1.3	Green - off grid	Overhead static -arable farming	4.30	55.66

2.3		Overhead static - permanent crops	4.27	57.25
3.3		Interspace vertical	4.17	65.11
4.3		Overhead dynamic	4.36	54.03

Figure 14 visualizes the LCOH of all the system configurations. Regarding LCOH, interspace vertical with the auxiliary grid to sell is the most suitable configuration with a LCOH of 3.67 Eur/kg (328.12 Rs/kg according to the conversion rate shown in Table 13).

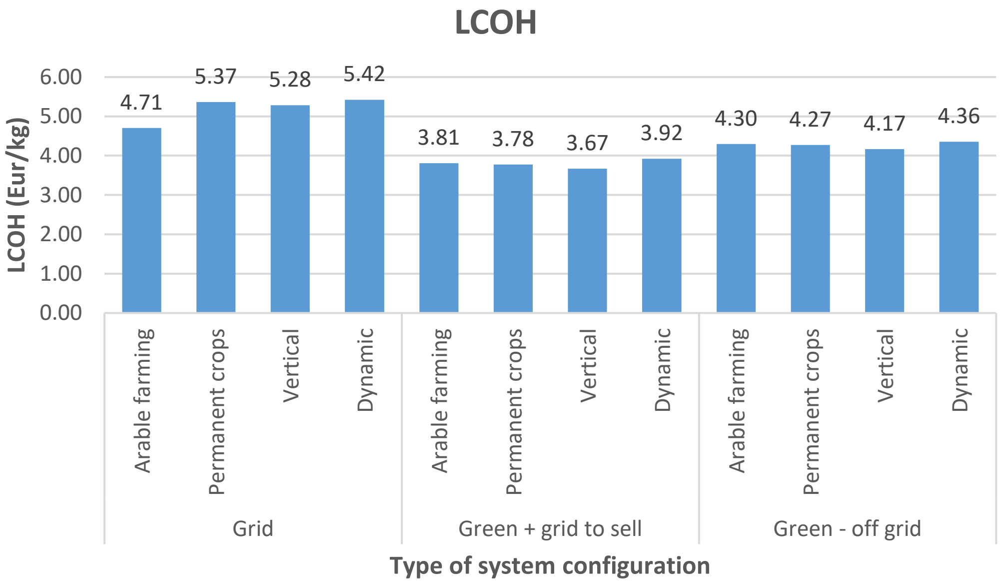


Figure 14: Representation of LCOH in respect to the type of system configuration; Source: Own creation

Grid hydrogen comparatively has the higher LCOH values for all the system configurations. This is primarily because the grid systems are buying considerable amount of electricity from the grid to generate the considerable amount of extra hydrogen as seen in Table 17. The electrolysers are forced to run at full load to generate uniform amount of hydrogen and to avoid the high contractual penalties due to non-deliverance of hydrogen. The off-grid systems were not able do so as analysed below. Unmet load for the grid systems is 0.13 % as seen in Table 17. As already described in section 3.1, the last 5-10% of the load represents a substantial portion of the total system costs which in also evident in the higher LCOH values for these systems.

Hence, the grid systems also have a negative NPV compared to the other systems. NPV in this study does not consider the effect of various subsidies available for such systems as well as the income from crop yield in agrivoltaics. Agrivoltaics or renewable energy in general is subject to government subsidies which also could not be directly considered in the software. Hence, the financial analysis done by the software is not the most accurate representation of such a case study when it will be implemented on ground. In the context of this study, case 1 is if the agrivoltaics system would be implemented by individual farmers then they would get assistance through the SKY scheme in Gujarat as explained in section 3.2. The project developer of the hydrogen project would then contract this electricity from the farmer to produce hydrogen. Hydrogen project with wind energy generator would then be subject to subsidies under the green hydrogen mission as explained in section 1.1. Case 2 is when the hydrogen project developer would also finance the agrivoltaic systems by leasing land from farmers where they would be subject to just the subsidies under the green hydrogen mission. These subsidies have not been accounted for in the software when optimizing the different system combinations. As the inclusion of subsidies would affect all cases equally it should theoretically not affect the comparative results and optimized system combinations. The overall value of NPV would increase by a small percentage and the LCOH will reduce accordingly. Monetary gain from the crop yield would also impact the results similarly. Internal Fraunhofer ISE analysis has shown that when considering just the economics of an agrivoltaics system, the contribution of the crop yield is not as significant as the contribution from selling the excess electricity to the grid. Hence, it can be safely assumed that not including the income from crop yield in the final analysis will affect the results but not to a significant extent. The extent at which it affects should be studied further along with the impact of the subsidies. NPV can’t be directly compared amongst the different system configurations as they generate considerably different amount of hydrogen influencing the acquisition costs of the components and electricity bought from the grid and incomes of selling hydrogen from these systems. Analysis has been conducted below where the system configurations have been compared when they would theoretically generate the same amount of hydrogen.

Figure 15 depicts the average LCOH for the three-system configuration. The green + grid to sell variants have comparatively lower LCOH as they have revenue from not only selling hydrogen like the grid systems but also the extra electricity. LCOH of the grid systems 5.19 €/kgH2 is 37 % and 22 % higher than the average LCOH values for green + grid to sell and green off-grid variants respectively.

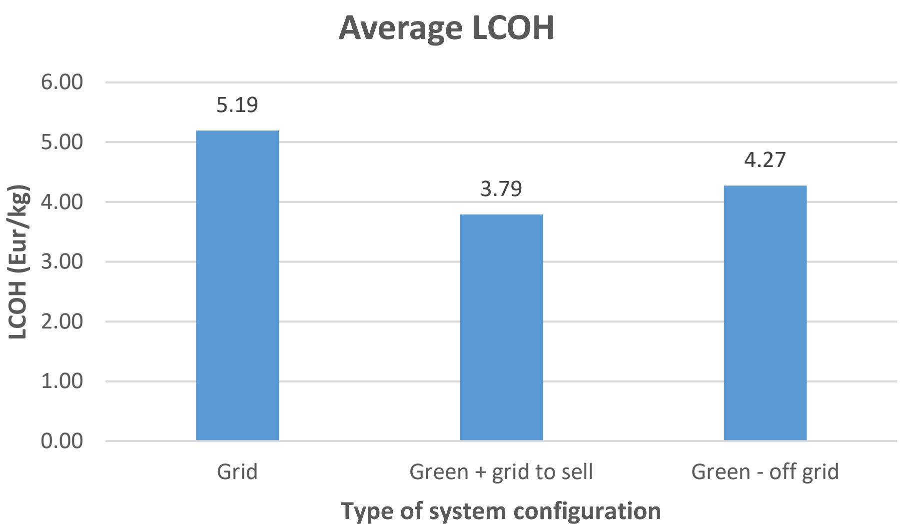


Figure 15: Representation of average LCOH in respect to the type of system configuration; Source: Own creation

Table 17 shows the results obtained in detail. Parameters in the table are annual values averaged over the system lifetime. Individual parameters have been analysed below and this Table has been included for reference. Key takeaway from this table is the difference in hydrogen generated per system configuration with respect to the number of PV generators. Off-grid arable farming and overhead dynamic system configuration utilize almost half the number of PV generators i.e., 60 MW less than the interspace vertical grid to sell system configuration to generate the same amount of hydrogen. The LCOH for the interspace system is though 15% and 16% less than the arable farming and overhead dynamic off grid system configuration respectively due to its lower acquisition cost. Hence, the off-grid configurations are more resource efficient but not cost-efficient in this regard. Parameters included in the table are:

- Eren - Energy generated by renewable sources
- Number of PV generators selected in the system
- Number of wind generators selected in the system
- Esell - Energy that can be sold to the grid
- Ebuy - Energy purchased from the grid
- Hgen - Hydrogen generated
- Unmet Load by the system

Table 17: Detailed results obtained in respect to the type of system configuration; Source: Own creation

Version	Type of hydrogen	Type of agrivoltaics	Results							
			Eren	Number of PV generators (each of 1 MW)	Number of wind generators (each of 2 MW)	Battery Capacity	Esell	Ebuy	Hgen	Unmet Load
			GWh/yr	No.	No.	MWh	GWh/yr	GWh/yr	tonnes/yr	%
1.1	Grid	Arable farming	300.165	86	32	0	44.541	179.268	5130.12	0.13
2.1		Permanent crops	326.977	114	32	0	56.449	174.373	5130.96	0.13
3.1		Interspace vertical	313.328	128	32	0	46.922	170.559	5131.57	0.13

4.1		Overhead dynamic	321.677	86	32	0	53.639	170.276	5131.63	0.13
1.2	Green + grid to sell	Arable farming	307.606	90	32	10	55.404	0	2627.36	4.89
2.2		Permanent crops	312.229	105	32	10	56.178	0	2645.43	4.89
3.2		Interspace vertical	313.328	128	32	10	53.41	0	2736.52	4.89
4.2		Overhead dynamic	309.014	80	32	10	52.642	0	2709.29	4.87
1.3	Green - off grid	Arable farming	259.236	64	32	10	0	0	2443.81	4.89
2.3		Permanent crops	264.709	76	32	10	0	0	2468.79	4.89
3.3		Interspace vertical	275.45	100	32	10	0	0	2581.42	4.89
4.3		Overhead dynamic	266.804	60	32	10	0	0	2536.83	4.87

All systems were designed with a 300 % buffer which ensured oversizing of the systems as explained in section 3.2. Minimum hydrogen to be produced annually was set as constraint at 2000 tonnes/year. The off-grid systems just about met this constraint. The electrolysers were selected to run at full load as stated previously. The off-grid variants were not able to do so as evident in the amount of hydrogen generated. The grid systems produced comparatively the most hydrogen as the electrolyser runs at full load in this variant as seen in Figure 16. The amount of hydrogen produced is almost the same in both configurations of the off-grid system due to the limitation from the over-sizing constraint as mentioned previously.

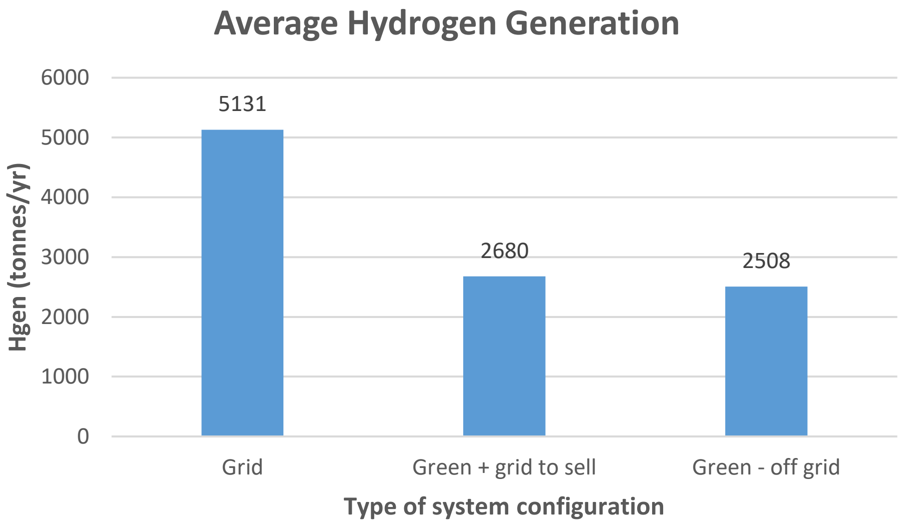


Figure 16: Representation of hydrogen generated in respect to the type of system configuration; Source: Own creation

All optimum solutions used the electrolyser of 40 MW which was the highest amongst the options available. It can be safely concluded by observing the first 50 solutions for all configurations that the software prefers to use the electrolyser with the highest capacity for minimizing LCOH.

The grid systems were considered with one week of hydrogen storage and the off-grid systems with one month of hydrogen storage. In order to compare these three variants when they produce almost the same amount of hydrogen, all solutions obtained for the interspace vertical grid system were analysed and the most optimum solutions for all the electrolyser capacities have been represented in Figure 17 which shows change in LCOH with electrolyser capacity. 20 MW electrolyser generates 2573 tonnes of hydrogen per year which is almost like the other systems in Table 17. LCOH of 6.13 €/kgH2 is 62 % and 44 % higher than the average LCOH values for green + grid to sell and green off-grid variants respectively.

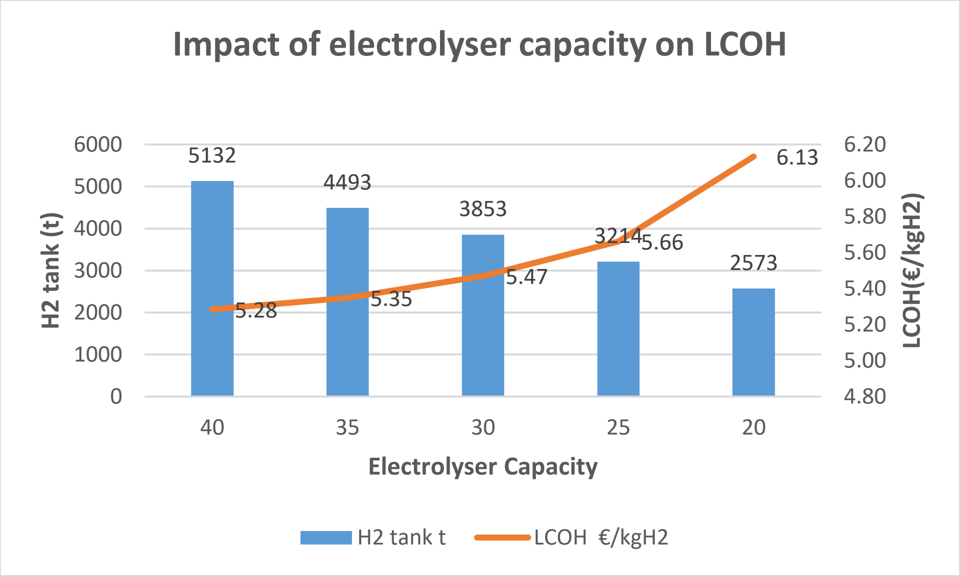


Figure 17: Representation of impact of electrolyser capacity on LCOH for interspace vertical grid system; Source: Own creation

The software can theoretically also utilize more battery storage in the off-grid systems to operate the 40 MW electrolyser always at full load to produce as much hydrogen as generated by the grid systems. This condition was simulated by simulating the most optimum system configuration again by changing the minimum number of batteries in the system from 0 to 5. No change in result in terms of hydrogen generated was observed. The systems generated similar amount of hydrogen. The increased number of batteries just increased the investment and hence, the LCOH. The software did not consider cycling the battery to produce more hydrogen. It was expected that the software will increase the number of renewable energy generators selected and store the excess energy in the increased battery capacity. This would then be cycled to run the electrolysers at full load when renewable energy is not available. The software did not consider the income from selling the hydrogen or electricity to compensate for the increased cost of cycling the excess energy through the batteries. This was also observed in the literature as stated in section 3.2.1 where battery storage was rarely a part of the optimum system configuration. This was also observed previously when sizing the system as stated in section 3.2.1. Oversizing of 200% was observed to increase the LCOH by 10 % due to increase in the battery capacity and 250 % oversizing increased the LCOH by 4 % but it reduced the electrolyser capacity selected thus producing less hydrogen. Batteries play a key role in the ramp up and ramp down phases of the electrolysers as also observed in the hourly generation profiles of different systems shown in section 4.3.1.2.

The grid systems do not have any battery selected and the off-grid systems selected the lowest possible amount of 10 MWh. The optimum solution of green + grid interspace vertical system uses 1 battery of 10 MWh. Another similar simulation was simulated with increased steps of 2 MWh of available battery capacity to design the battery storage capacity in more detail. Results observed were exactly like the previously simulated scenario. The optimum system selected 5 batteries of 2 MWh each totalling to the previously selected 10 MWh. Hence, 10 MWh is the minimum required battery capacity for the optimum systems considering the ramp up and ramp down requirements of the selected electrolyser capacity.

All the variants have almost the same amount of renewable energy generation as seen in Figure 18 and the same wind energy generation. The optimum systems generate as much energy to run the electrolyser and fulfil the load demand and meet the constraint of minimum hydrogen to be generated. All the optimum systems have the maximum number of available wind energy generators. Number of PV generators selected is proportional to the cost of the generator i.e interspace vertical has the highest number and overhead dynamic the lowest number in all the three cases. Increasing the oversizing enabled the optimum systems to have higher number of renewable energy generators as seen from the simulation result analysed below.

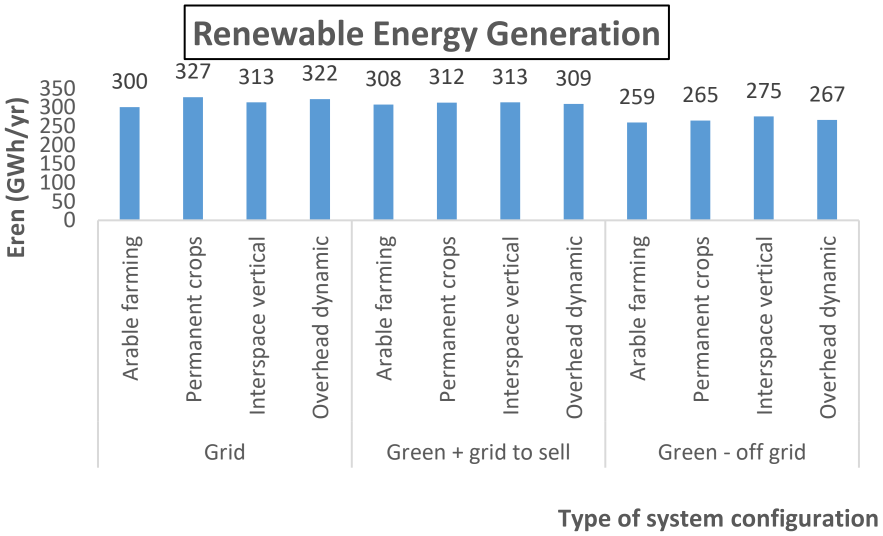


Figure 18: Representation of renewable energy generated in respect to the type of system configuration; Source: Own creation

The off-grid systems could also be oversized more to produce as much hydrogen as the grid system. Changing the oversizing from 300 % to 2500 % generated equivalent amount of hydrogen but the LCOH increased exponentially due to the increased direct investments due to the increase in number of renewable energy generators selected. Hence, the increase in oversizing did not optimize the system combination further as it is already optimized to meet the constraints with the lowest LCOH.

4.2 Impact on LCOH with reduced cost of storage

Previously mentioned Fraunhofer country study for different power-X products stated that the most cost-effective storage solution for large amounts of pressurized hydrogen storage is underground salt caverns, which come with investment costs of below 10 EUR/kg of hydrogen storage capacity. (Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023) This is 98% less than cost of tank storage considered in this study at 500 Eur/kg. However, underground salt caverns require special geological structures which are not generally available. Storage cost accounts for almost 5 % of the acquisition cost of the electrolysers in this study. The acquisition cost for the most suitable system configuration from this study i.e green + grid to sell interspace vertical was reduced by 98% to analyse the impact on the LCOH. It was observed that the LCOH reduces by 1 %. This is not a significant difference in regard to reducing the cost of produced hydrogen. The size of hydrogen storage was not a point of consideration in this study. Tank storage sizes increase exponentially with storage capacity which will be a point of concern with increasing generation capacities in the future. Hence, cheaper and size efficient storage options need to be developed for these increased capacities. Similarly, simulations with reduced cost of battery storage were run. Scaling factors for CAPEX of battery storge were calculated for the sensitivity analysis of future projection scenarios of 2040 and 2050 as explained in section 3.2.1. Scaling factors of 0.47 and 0.31 reducing the CAPEX of the battery storage accordingly were used in these simulations. LCOH reduced by 1 % in both the cases. The optimized solution though still did not increase the capacity of battery storage to produce more hydrogen similar to the cases explained previously. This denotes that even the reduced cost of battery storage was not enough for the optimized simulation to select increased capacity of battery storage to cycle the excess electricity to produce more hydrogen.

4.3 Analysis for all agrivoltaic system types

Table 18 shows the same results obtained but in respect to the different agrivoltaic system types. These are the results for the base case of 2024. As seen previously the interspace vertical grid to sell configuration has the lowest LCOH in green compared to the other system types who have comparatively similar LCOH values in respect to the configuration of hydrogen production. Reasons for the same have been analysed below.

Table 18: Results obtained in respect to the type of agrivoltaic system; Source: Own creation

Version	Type of agrivoltaics	Type of hydrogen	Results	
			LCOH	NPV
			€/kg	M€
1.1	Overhead static -arable farming	Grid	4.71	-61.10
1.2		Green + grid to sell	3.81	85.49
1.3		Green - off grid	4.30	55.66
2.1	Overhead static - permanent crops	Grid	5.37	-14.23
2.2		Green + grid to sell	3.78	87.93
2.3		Green - off grid	4.27	57.25

3.1	Interspace vertical	Grid	5.28	-5.42
3.2		Green + grid to sell	3.67	96.99
3.3		Green - off grid	4.17	65.11
4.1	Overhead dynamic	Grid	5.42	-20.24
4.2		Green + grid to sell	3.92	81.51
4.3		Green - off grid	4.36	54.03

Interspace vertical green + grid to sell is the most suitable configuration in regard to LCOH of 3.67 Eur/kg (328.12 Rs/kg according to the conversion rate shown in Table 13) as also stated previously. In relation to NPV, this system has the highest value of 96.99 M€ (867 Rs crore according to the conversion rate shown in Table 13) Figure 19 visualises the average LCOH for all the system types. Overhead static – arable farming has the lowest average LCOH value. This is because the grid configuration for this system has significantly lower LCOH compared to the other systems in the grid configuration as seen in Table 18. This is because it has significantly a smaller number of PV generators of 86 compared to 128 in permanent crops and interspace vertical system as seen in Table 17. It has the same number of PV generators as the overhead dynamic system but the CAPEX here is 21 % lower than the dynamic system. This was also the key takeaway from Table 17 as seen previously. Overhead static and dynamic systems are more resource efficient due to their higher energy generation capacities of 5.58 kWh/m2 and 6.37 kWh/m2 compared to 4.87 kWh/m2 and 3.96 kWh/m2 of the overhead permanent crop and interspace vertical system type respectively. This points to need of research in optimizing the mounting systems for the overhead dynamic and arable farming systems to reduce their acquisition cost. Regions with space constraints will have to utilize these system types as they utilize on an average almost half the number of PV generators as seen in Table 17. The software gives higher weightage to the acquisition cost compared to the generation capacities as seen in the optimum systems for all system configurations in this study. This result was also observed in the hourly profiles of all system types analysed in section 4.3.1.2.

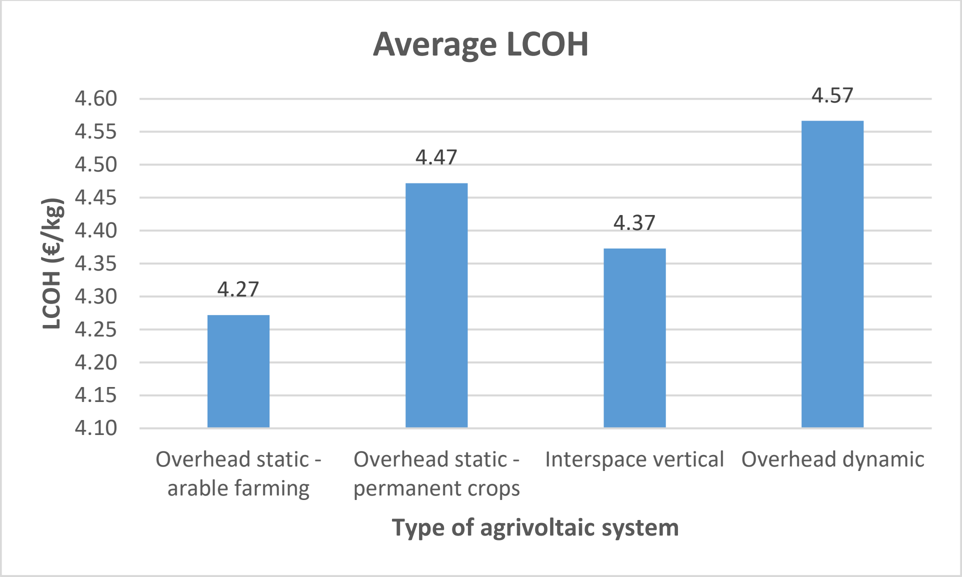


Figure 19: Representation of average LCOH in respect to the type of agrivoltaic system; Source: Own creation

Table 19 shows some the results obtained in detail. Parameters in the table are annual values averaged over the system lifetime. The key takeaway from this table is that even though the number of PV generators is different for the different system types the investments are almost the same due to the differences in their acquisition cost. Individual parameters have been analysed below. Parameters included in the table are:

- Total investment in Million Euros
- Internal rate of return or IRR - This indicates the profitability of a project. It is the rate at which a project breaks even.
- Capacity factor - Capacity factor represents the ratio of actual to theoretical output.
- Payback period - In NPV maximization systems, it is calculated as the ratio between the investment cost and the net incomes of the first year. (Dr. Rodolfo Dufo López, 2024b) It represents the time it takes for the initial investment of the project to be paid off with its revenue.

Table 19: Detailed results obtained in respect to the type of agrivoltaic system; Source: Own creation

Version	Type of agrivoltaics	Type of hydrogen	Results			
			Investment	**IRR**	**Capacity Factor**	**Payback**
			M€	**%**	**%**	**yr**
1.1	Overhead static - arable farming	Grid	147.389	0.00	15.51	25
1.2		Green + grid to sell	152.373	12.05	11.80	13.01
1.3		Green - off grid	136.357	10.95	8.63	14.62
2.1	Overhead static - permanent crops	Grid	154.605	0.00	16.59	25
2.2		Green + grid to sell	152.373	12.16	10.86	12.88
2.3		Green - off grid	137.061	11.02	7.97	14.51
3.1	Interspace vertical	Grid	149.325	0.00	14.81	25
3.2		Green + grid to sell	151.845	12.60	9.61	12.35
3.3		Green - off grid	139.833	11.37	7.11	13.95
4.1	Overhead dynamic	Grid	161.579	0.00	19.47	25
4.2		Green + grid to sell	159.413	11.69	12.66	13.46
4.3		Green - off grid	143.793	10.71	9.24	14.97

The payback period of all systems is very similar with respect to the system configuration. Figure 20 shows the average investment of all the agrivoltaic systems considered. All the investment values are in a comparably similar range with overhead dynamic system being slightly higher than the others. This is because of the higher CAPEX of the overhead dynamic PV generator compared to the other generators as the number of all other components is same for all system types. The number of PV generators differ as described previously and shown in Table 17.

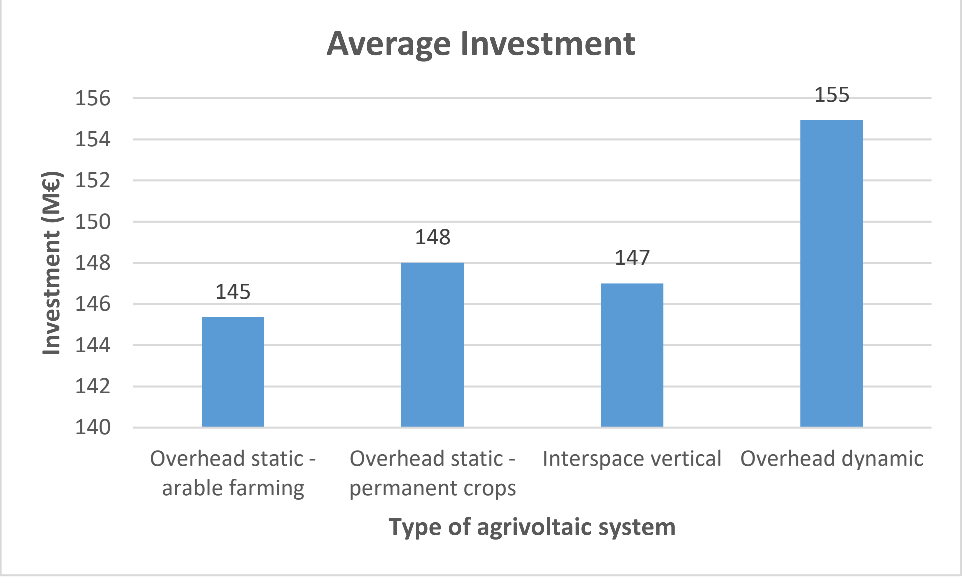


Figure 20: Representation of average investment in respect to the type of agrivoltaic system; Source: Own creation

Figure 21 visualises the IRR for all the systems. The grid system configuration has zero IRR for all the systems because of the negative NPV values. Rest of the systems have similar IRR values with green + grid to sell interspace vertical configuration having the highest value. This is in the range of IRR values for solar projects in India. According to a study on solar projects in India by Gulia, equity IRR of more than 14% was considered good, but now with falling tariffs and increasing competition, most developers are estimated to be getting equity return of 12-13%. (Jyoti Gulia, 2020)

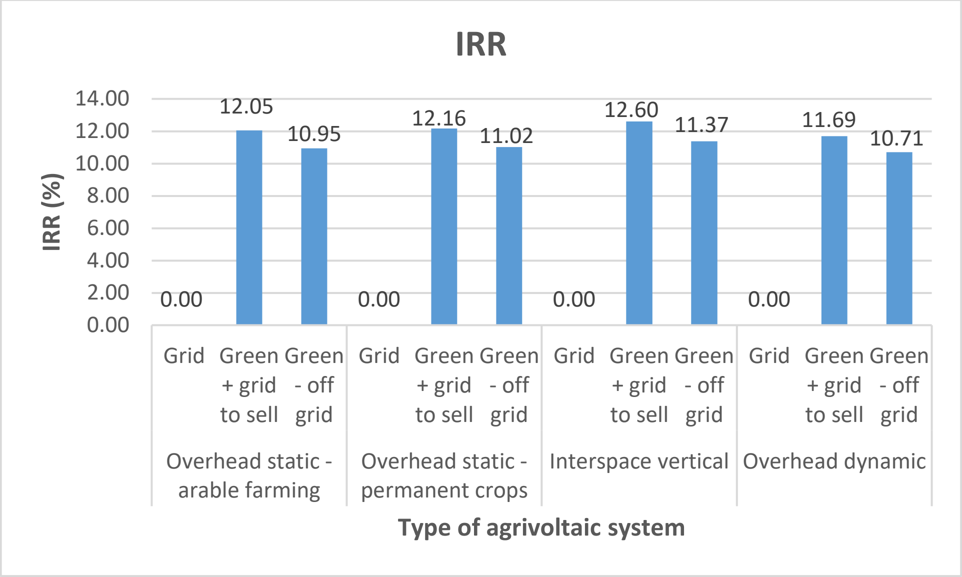


Figure 21: Representation of IRR in respect to the type of agrivoltaic system; Source: Own creation

Figure 22 visualises the capacity factor for all the systems. The overhead dynamic systems in general have the highest capacity factors for all the system configurations. Government of India report on energy capacity mix for 2029-30 considered capacity utilization factor values for different region in India for solar and wind energy. Average of these values was calculated to be 21% and 25% for solar and wind energy respectively. Capacity utilization factor considers installed capacity compared to the maximum theoretical output considered in capacity factors. Capacity factors for the systems simulated in this study are comparatively lower. Point to note is that these are capacity factors for the overall system with electrolysers not operating at full load in most of the cases. The grid configurations where the electrolyser does operate at full load have comparative higher values with overhead dynamic having the highest of 19.47. The off-grid systems have comparatively low values of the capacity factor as they do not have the option of selling excess electricity to the grid. Hence, the renewable energy generators cannot operate at full theoretical capacity.

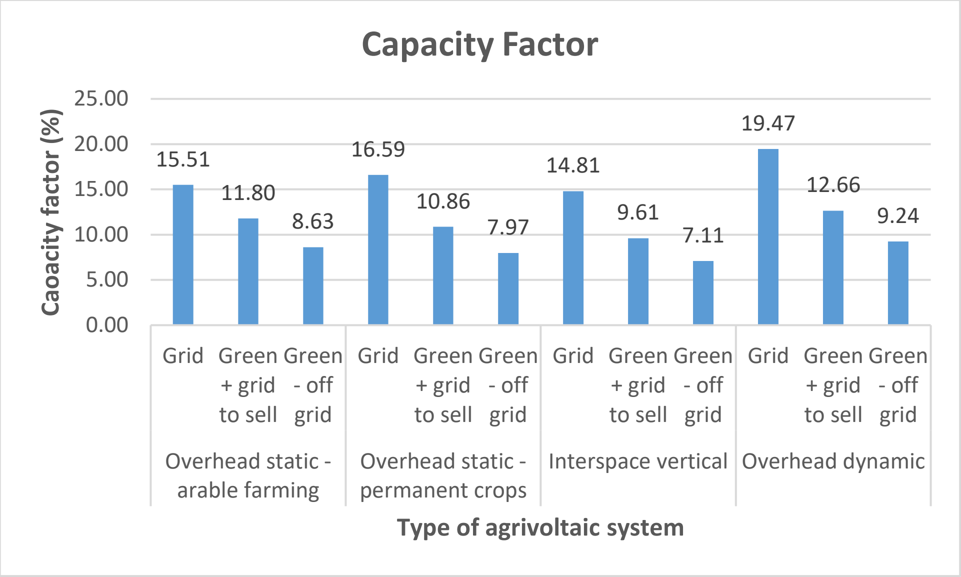


Figure 22: Representation of capacity factor in respect to the type of agrivoltaic system; Source: Own creation

4.3.1 Comparative analysis for uniformity of hydrogen and power generation

Considering the penalties imposed for non-supply of the hydrogen demand by the industries, other part of objective 2 of this study as stated in section 1.2 is generation of uniform hydrogen throughout the year. This has been analysed with the help of the following graphs from the software. Uniformity of energy generation for the different agrivoltaic system types has also been analysed in this section.

4.3.1.1 Uniformity in hydrogen production

Figures below show the monthly hydrogen production by the electrolysers. As seen before all grid and off-grid configurations have almost similar uniform hydrogen generation per system type respectively throughout the year. This is because as stated before the electrolysers were selected to run at full load all the time and the grid provides the required excess energy when there is a shortage in generation of the renewable sources. Figure 23 shows the annual hydrogen generation for interspace vertical grid, green + grid to sell and arable farming green + grid configuration respectively. They are similar in respect to the hydrogen system configuration irrespective of the agrivoltaics system type and orientation. Graphs for all configurations have been provided in the Annex for reference.

Figure 23: Monthly hydrogen production for interspace vertical grid, green + grid to sell and arable farming green + grid to sell system configuration; Source: MHOGA software snapshot

Rest of the agrivoltaic systems show similar results. This shows that the amount of hydrogen generated is comparatively same for all system configurations irrespective of the agrivoltaic system type.

4.3.1.2 Uniformity in average power generated

Figures below show the monthly and annual average power generated by the renewable energy generators and energy sold to the grid in cases where this option is available. Monthly power produced is observed to have similarly uniform pattern in all cases. Energy sold to the grid is also uniformly in corelation with the power produced in all configurations. Figure 24 shows the monthly and annual average power for interspace vertical grid, green + grid to sell and off-grid system configuration respectively. Graphs for all configurations have been provided in the Annex for reference. Peak average power produced changes in respect to the type of hydrogen configuration, but the annual distribution profile of the power produced stays the same.

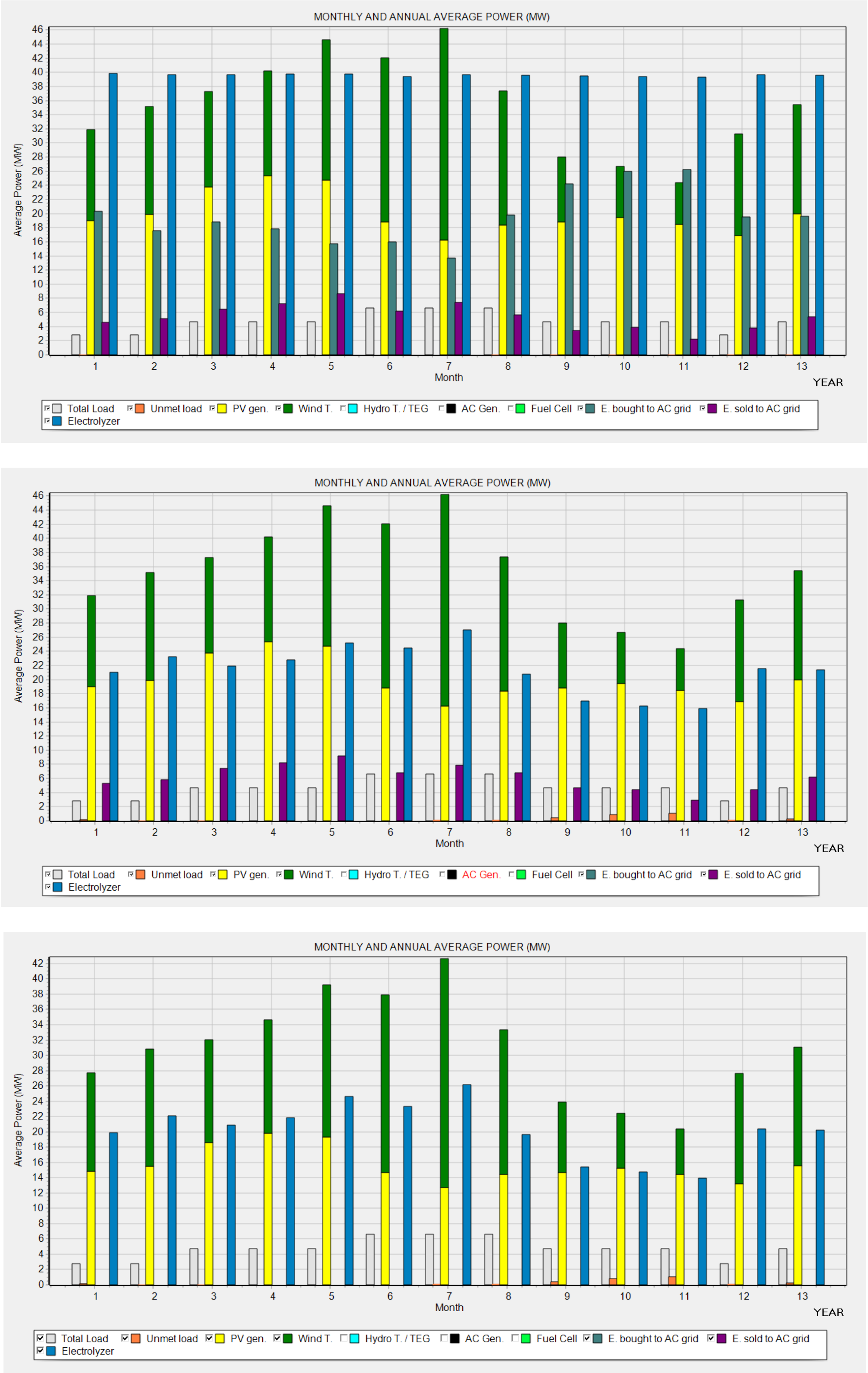


Figure 24: Monthly and annual average power for interspace vertical grid, green + grid and off grid system configuration; Source: MHOGA software snapshot

Unmet load is observed to be higher in the months of September, October, and November in which the amount of wind generation is lower. Electrolyser also operates at significantly reduced capacity in these months as the overall renewable generation is also the lowest in these months. This highlights the importance of higher capacities of hydrogen storage and flexible hydrogen demand and flexible use-cases to counteract the intermittent nature of renewable energy. Figure 25 shows the hourly profile for 1st January for grid overhead static- permanent crops and interspace vertical system respectively.

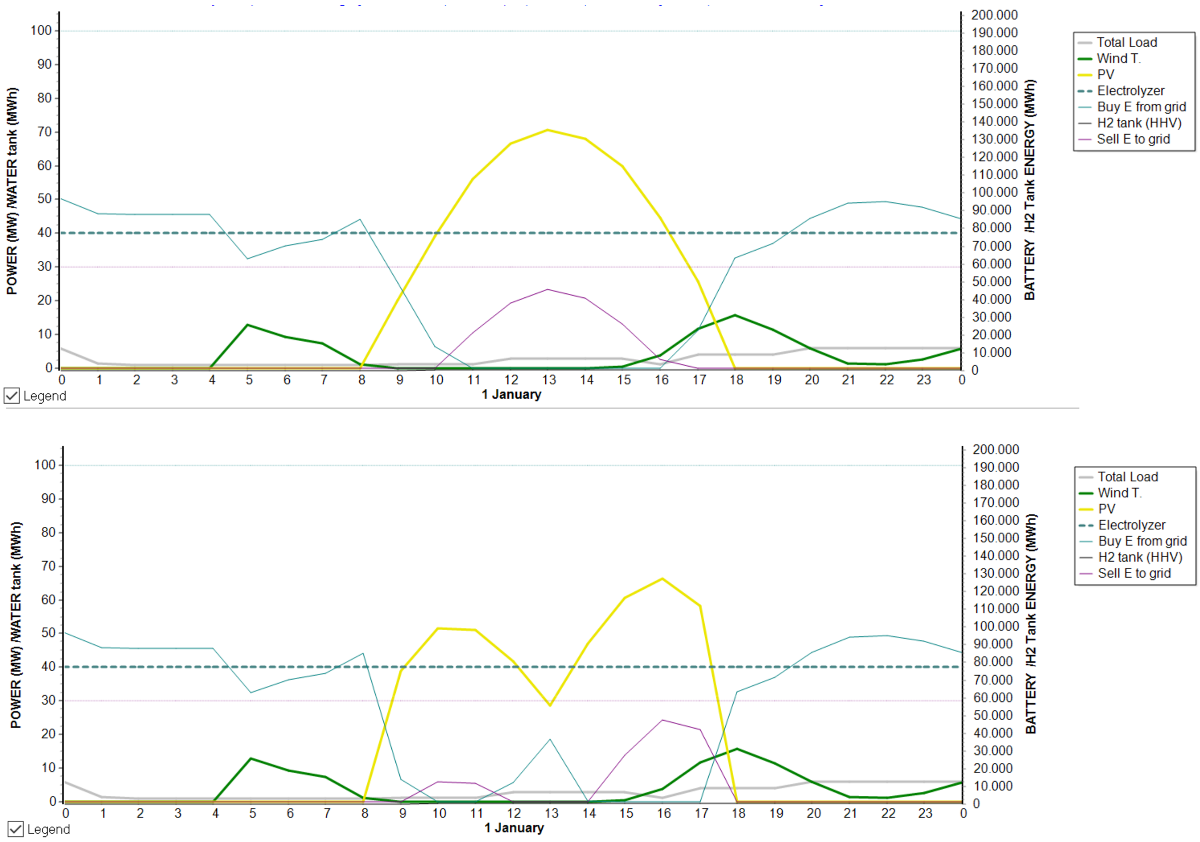


Figure 25: Hourly profile for overhead static- permanent crops and interspace vertical grid system configuration: Source: MHOGA software snapshot

The different peaks in the PV generation profiles can be observed here. This directly impacts the electricity bought from and sold to the grid. More electricity is sold to the grid during morning and evening hours for the interspace system compared to the peak afternoon hours for the south facing systems. Electricity is then conversely bought from the grid. There is also an increase in the energy bought from the grid at the times when the renewable energy is not produced and when the load demand increases during the evening and night hours. Figure 26 shows the profiles of the same two agrivoltaics systems respectively for the green + grid to sell configuration. Graphs for all configurations have been provided in the Annex for reference.

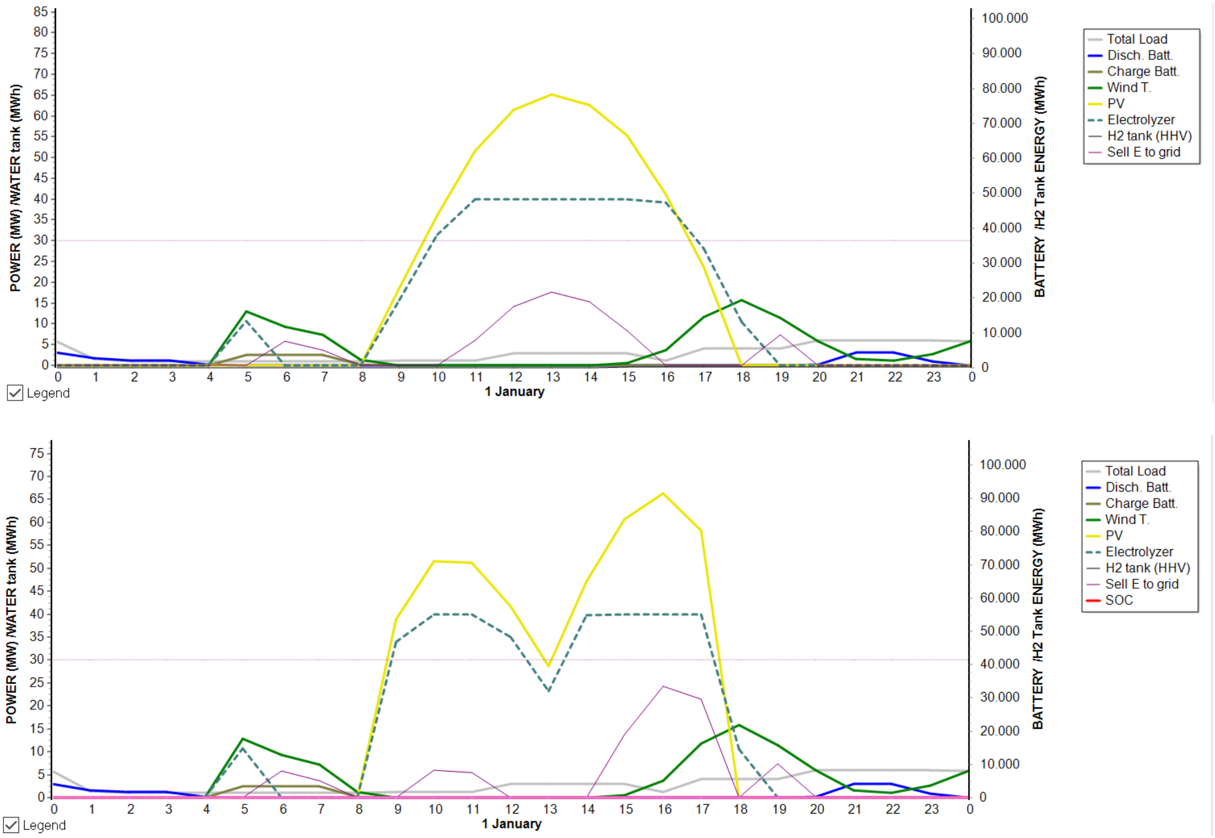


Figure 26: Hourly profile for overhead static- permanent crops and interspace vertical green + grid to sell system configuration: Source: MHOGA software snapshot

Profiles of renewable energy generation and energy sold to the grid are the same as before. Batteries discharge during the morning and the night hours when renewable energy is not available and charge when the wind energy generation is at its peak. Batteries are active during the ramp up and ramp down phase of the electrolyser. The electrolyser profile closely follows the renewable energy generation profile. Hence, uniform hydrogen production seems to be not dependent predominantly on the type of agrivoltaic system. The software optimizes the number of PV generators based on the acquisition cost more compared to the generation profile of the PV generators.

The profile of the energy sold to the grid might play a key role in selecting the type of agrivoltaic system. As green hydrogen production increases the supply and demand profile to/from the grid will get affected. Interspace vertical system has a comparatively different profile of energy sold to the grid with the peaks in the morning and afternoon hours and lowest acquisition cost producing the same amount of hydrogen as the other systems. Hence, interspace vertical system green + grid to sell configuration seems to be the most suitable for cost-efficient hydrogen production. The uniformity of hydrogen supply is ensured with longer duration of storage in the off-grid system configurations compared to the grid configurations.

4.4 Impact on LCOH with increased revenue from oxygen

As highlighted in section 2.4, use of the by-product oxygen from the hydrogen generation process for aquaculture or in manufacturing industries needs to be further explored at a pilot scale. The basic stoichiometric balance indicates that approximately 8 kg of oxygen, with a purity level exceeding 99%, is produced for every kg of hydrogen. (Moe Thiri Zun, Benjamin Craig McLellan, 2023) Compressed oxygen of high purity (grade 4.5) can cost up to 4.4 USD/kgO2 (4.12 Eur/kgO2 according to the conversion rate shown in Table 13), and prices for medical use are even higher due to stringent quality control measures to ensure minimal impurities. (Moe Thiri Zun, Benjamin Craig McLellan, 2023) Most optimum configuration of interspace vertical green + grid to sell was re-simulated by considering additional revenue from selling oxygen. Additional revenue from selling oxygen at 4.12 Eur/kgO2 at 5.13 % inflation rate, the same as hydrogen was added. NPV increases by almost 2000%. The software cannot calculate the change in LCOH as it does not directly include this in the calculation. Oxygen produced by electrolysis process can provide an additional revenue from electrolysis and further help reduce the LCOH.

4.5 Analysis of future projection scenarios

Sensitivity analysis for the most optimum configuration of interspace vertical for green+ grid just to sell was conducted and Table 20 shows the results obtained. It projects the change in LCOH for 2040 and 2050.

Table 20: Results obtained by sensitivity analysis; Source: Own creation

Version	Type of hydrogen	Type of agrivoltaics	Result		
			LCOH		
			€/kg		
			Base	2040	2050
3.2	Green + grid to sell	Interspace vertical	3.67	3.12	2.80

Average decrease in LCOH for 2040 is 15 % and for 2050 is 24 % compared to the base case. It achieves LCOH of 3.12 Eur/kg (279 Rs/kg according to the conversion rate shown in Table 13) in 2040 and 2.80 Eur/kg (250 Rs/kg according to the conversion rate shown in Table 13) in 2050. The optimum system in 2050 is the first optimum system analysed in the study which did not select the maximum number of wind energy generators available. This system selected 18 wind generators instead of the 32 selected in all other configurations. This system also had a higher battery capacity of 30 MWh compared to the 10 MWh of the other configurations. Though, a point to note is that it also selected the electrolyser of 35 MW compared to 40 MW electrolysers in the other system configurations. Investment for the system configuration in 2050 reduced significantly by 43% compared to the base case of 2024. As described in section 3.2.1 and shown in Table 14, sensitivity analysis factors for wind and batteries were 0.93 and 0.47 in 2040 respectively and 0.90 and 0.31 in 2050 respectively. It can be deduced that the reduction in CAPEX for wind in 2050 is comparatively less significant compared to the reduction in batteries. It was already observed that these hybrid configurations were PV dominated for the base cases of 2024 and this trend just increases in 2040 and 2050. This result also highlights that agrivoltaics + hydrogen system configuration would need support in the form subsidies to have a LCOH below 2 Eur/kg until both technologies are technologically mature.

5 Conclusion

The most studied use cases for green hydrogen in agriculture were found to be as a part of objective 1 of this study: source of energy for agricultural activities and machinery, use of the by-product oxygen in fish breeding and use of green ammonia as fertilizer.

MHOGA Pro+ was successfully tested and approved for designing combined agrivoltaics + H2 production systems and the discovered bugs have been since acknowledged and resolved by the developers of the software.

Interspace vertical system type is the most suitable system in this context for cost-efficient production of hydrogen with agrivoltaics.

Interspace vertical with the auxiliary grid to sell excess electricity is the most suitable configuration with a LCOH of 3.67 Eur/kg or 328.12 Rs/kg. It drops to 2.80 Eur/kg or 250 Rs/kg in 2050.

Off-grid arable farming and overhead dynamic system configuration utilize almost half the number of PV generators i.e., 60 MW less than the interspace vertical grid to sell system configuration to generate the same amount of hydrogen making them more resource efficient. The LCOH for the interspace system though makes it more cost efficient as it is 15% and 16% less than the arable farming and overhead dynamic off grid system configuration respectively due to its lower acquisition cost.

It was observed that these hybrid configurations were PV dominated for the base cases of 2024 for all system configurations and this trend increases in 2040 and 2050. Investment for the system configuration in 2050 reduced significantly by 43% compared to the base case of 2024.

Systems considered in this study are not just purely hydrogen generating systems due to the considered load but nevertheless, hydrogen produced with agrivoltaics will require support in form of subsidies to have a price below 2 Eur/kg. Oxygen produced by electrolysis process can provide an additional revenue and further help significantly reduce the LCOH by increasing the NPV by almost 2000 %.

The electrolyser hourly production profile was observed to closely follow the hourly renewable energy generation profile irrespective of the type or orientation of the system. Hence, uniform hydrogen production seems to be not dependent predominantly on the orientation of the agrivoltaic system but instead more on its acquisition cost.

6 Outlook

MHOGA was used in this study due to its functionality of various control strategies for grid connected batteries and electrolysers and for also being able to simulate selling the surplus hydrogen produced. MHOGA has limitations in simulating an agrivoltaic system compared to a ground mounted PV system. Agrivoltaics provides an additional income to the farmers by leasing of land to project developers in addition to their traditional income from crop yield. Both incomes could not be directly considered in the analysis by the software. This would require a case and region-specific financial analysis external to the software which would be conducted as part of future study to exactly contextualize the synergy between agrivoltaics and green hydrogen at a regional level.

Specific information on the crops growing at the location of the study and crop yield simulations to assess the effect of agrivoltaics on the yield of these crops would be needed to compare the suitability of such systems to not only produce cost-efficient hydrogen which was the objective of this study but also crop-efficient hydrogen which will be the objective of future studies.

Off-grid arable farming and overhead dynamic system configuration utilize almost half the number of PV generators to generate the same amount of hydrogen making them more resource efficient. The LCOH for the interspace system though makes it more cost efficient due to its lower acquisition cost. System configuration with a combination of these two or three system types can provide the benefits of both by being resource and cost efficient. This would be one of the cases simulated in the follow up study to analyse the extent of the benefit of such a system configuration and the optimum ratio of number of generators amongst the different system types.

Tax on grid electricity or carbon emission from grid electricity was not considered in this study for the future cost projections in the sensitivity analysis. In the previously introduced study on analysing the commercial feasibility of a green ammonia production plant in India, a carbon tax of 50 USD/ton (4183 Rs/tonne or 47 Eur/ton according to the conversion rate shown in Table 13) was used for simulating the scenario in 2030 compared to no tax in 2023 to make green ammonia economically feasible compared to grey ammonia. It was observed that the price difference between grey and green ammonia reduced to 8 % in 2030 (Green ammonia cost of 702 Eur/ton and grey ammonia cost of 646 Eur/ton in 2030 according to the conversion rate shown in Table 13) compared to 31% in 2023. It was concluded that without any carbon tax, green ammonia will only be viable in India only at an elevated gas price and low renewable electricity cost for electrolysis. (Deloitte, 2023) It can be stated that such an imposition of carbon tax would be necessary to promote the use and increase the uptake of green hydrogen as well and reduce the dependency on electricity grid moving forward. The effect such a tax on the LCOH needs to be analyzed in a detailed financial analysis external to the software in future studies.

The legal and policy framework around agrivoltaics and green hydrogen is still developing in India just like many other countries around the world. Indian government has directed the state governments to provide suitable tax and duty structures wherever possible for the promotion of green hydrogen projects. (MNRE, 2023) This is already evident in the green hydrogen policy developed by Andhra Pradesh, another state of India. The state government here provides 100% reimbursement of tax on the sale of green hydrogen or green ammonia in the state for five years. It also provides 100% exemption of electricity duty for the power consumed for production of green hydrogen or green ammonia for the same duration from the date of commercial operation. (New and Renewable Energy Devpt. Corp. of Andhra Pradesh Ltd., 2023) The effect of such incentives on the cost of hydrogen have not been considered in this study. They should be considered when developing a project plan for implementing such a project on the ground and would require a case and region-specific financial analysis external to the software.

The Energy and Resource Institute of India (TERI) in their study included an analysis of a cluster in Gujarat, India where there is a concentration of chemical and petrochemical facilities, which produces hydrogen at 288 Rs/kg (3.22 Eur/kg according to the conversion rate shown in Table 13) in 2020. They stated that the price of green hydrogen would fall to around Rs 152/kg by 2030 and Rs 93/kg by 2050 (1.70 Eur/kg in 2030 and 1.04 Eur/kg in 2050 according to the conversion rate shown in Table 13) if battery storage is included. Similarly, it would fall to Rs 178/kg by 2030 and Rs 114/kg by 2050 (1.99 Eur/kg in 2030 and 1.27 Eur/kg in 2050 according to the conversion rate shown in Table 13) with H2 tank storage. (Will Hall, 2020). The systems considered in this study are not purely hydrogen generating systems as the system considered in this TERI study. Wind energy and load to be supplied to surrounding villages were considered here to simulate a more realistic scenario to real world implementation. Nevertheless, hydrogen produced with agrivoltaics will require support in form of subsidies to be competitive in the market. LCOH of purely agrivoltaics hydrogen generating systems will be part of follow-up work from this study.

As analysed in section 4.4, oxygen produced by electrolysis process can provide an additional revenue from electrolysis and further help reduce the LCOH. The extent of this should be studied in the future with more research in an Indian context and in a detailed financial analysis external to the software.

As stated in section 2.4, agrivoltaics will contribute to multiple sustainable development goals. The impact of these goals was not within the scope of this study. Large scale semi off-grid H2 systems can help electrifying rural areas with almost free electricity because of income from H2. Feasibility of such a system to contribute to a specific local rural economy needs to studied in depth. A socio-economic study should be conducted which will not only cover the economic indicators covered in this study but will also quantify and compare the social impacts of such a system configuration.

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Annex

Table 21 provides an overview of steps performed to setup the simulations in the software.

Table 21: Steps to setup the simulations; Source: Own creation

Tab	Option	Comment and parameters defined
	Project - Options	
	Multiperiod simulation selected	Default data used for parameters
	Minimize LCOH	Min H2 to be produced annually
	General Data	
	Components	Selected - PV, wind, electrolyser, battery bank, inverter
	Maximum evacuation time changed	To evaluate all combinations
	Min and max parallel components set	
	Constraint for unmet load set	
	Load/AC Grid	
AC-Load -		
	Load Profile	Internal town load profile selected
Purchase/Sell E		
	V1.1,2.1,3.1,4.1 - Purchase and sell from/to grid checked	Fixed buy price, annual inflation, emmisions
	V1.2,2.2,3.2,4.2 - Only sell to grid checked	
	V1.3,2.3,3,3,4.3 - No grid (purchase & sell unchecked)	
	AC Grid Availability	Random generation of non-availability for 2% of time
	Priority to supply E not covered by renewables	Storage/Generator
	Resources -Solar	
	Location	
	Irradiation	File imported according to the versions (Generation normalized to 1 MWp)
		V1.1,1.2,1.3- arable.txt
		V2.1,2.2,2.3 - permanent.txt

		V3.1,3.2,3.3 - interspace.txt
		V4.1,4.2,4.3 - tracked.txt
Resources - Wind		
	Anemometer height	
	Wind speed	Downloaded Renewable Ninja data
Components -Wind		
	Height above sea level	
	Wind turbine general data	Changed cost parameters
Components -Solar		
	Changed standard PV 10 BIF module to 1 MWp	Changed cost parameters of module according to the version of simulation
Components -Fuel Cell/Electrolyser		
	Added 25 MW, 30 MW, 35 MW, 40 MW electrolyser	Changed cost parameters of electrolysers
	Compression electrical consumption changed	
Components -Batteries		
	Standard battery of 10 MWh	Changed cost parameters
Components -Inverters		
	Standard battery of 10 MW	Changed cost parameters
	Proportional to first inverter rated power selected	
Voltages		
	AC voltage changed	
Control Strategies		
	V1.1,2.1,3.1,4.1	Electrolyser at full load; Price E<>=0; Compare with sell price unchecked
	V1.2,2.2,3.2,4.2	Load following; Compare with sell price box checked,
	V1.3,2.3,3,3,4.3	Load following
Financial Data		
	Loan parameters set	
	Installation cost and variable initial cost	

	Extra cashflow added	To consider revenue from selling electricity to fulfill load demand
Sensitivity Analysis		
	Component cost analysis	Scaling factors set for 2 cases of 2040 and 2050

Table 22 provides an overview of the sources and values used to estimate the fixed buy price set in the Load/AC Grid tab.

Table 22: Fixed buy price parameter sources; Source: Own creation

Case	**Unit**	**Purchase from grid**	**Source**
	Eur/MWh	102	(Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023)
	Eur/kWh	0.102	
Average case	Rs/kwh	5.22	(Takuma Otaki, 2023)
	EUR/kWh	0.058	
Competitive case	Rs/kwh	2.675	
	EUR/kWh	0.030	
2020	Rs/MWh	6290	(Will Hall, 2020)
	EUR/kWh	0.070	
2030	Rs/MWh	5500	
	EUR/kWh	0.062	
2050	Rs/MWh	4810	
	EUR/kWh	0.054	
This study	EUR/kWh	0.077	

Table 23 provides an overview of the sources and values used to estimate the fixed sell price set in the Load/AC Grid tab.

Table 23: Fixed sell price parameter sources; Source: Own creation

Case	**Unit**	**Purchase from grid**	**Source**
	Rs/kwh	2.67	(J Charles Rajesh Kumar, MA Majid, 2023)
	EUR/kWh	0.030	
	Rs/kwh	2.69	
	EUR/kWh	0.030	
	Rs/kwh	2.69	
	EUR/kWh	0.030	

	Rs/kwh	2.9	
	EUR/kWh	0.032	
	Rs/kwh	2.41	
	EUR/kWh	0.027	
	Rs/kwh	2.41	
	EUR/kWh	0.027	
	Rs/kwh	2.41	
	EUR/kWh	0.027	
	Rs/kwh	2.42	
	EUR/kWh	0.027	
	Rs/kwh	2.34	
	EUR/kWh	0.026	
	Rs/kwh	2.34	
	EUR/kWh	0.026	
	Rs/kwh	2.34	
	EUR/kWh	0.026	
	Rs/kwh	2.35	
	EUR/kWh	0.026	
	Rs/kwh	2.53	
	EUR/kWh	0.028	
	Rs/kwh	2.88	
	EUR/kWh	0.032	
	Rs/kwh	2.88	
	EUR/kWh	0.032	
	Rs/kwh	2.89	
	EUR/kWh	0.032	
	Rs/kwh	2.94	
	EUR/kWh	0.033	
	Rs/kwh	2.94	
	EUR/kWh	0.033	
	Rs/kwh	2.99	
	EUR/kWh	0.033	

	Rs/kwh	3	
	EUR/kWh	0.034	
	Rs/kwh	3.24	
	EUR/kWh	0.036	
	Rs/kwh	2.59	
	EUR/kWh	0.029	
Average	Rs/kwh	2.68	
This study	EUR/kWh	0.030	

Table 24 provides an overview of the sources and values used to estimate the hydrogen sell price set in the Load/AC Grid tab.

Table 24: Hydrogen sell price parameter sources; Source: Own creation

Unit	**Value**	**Source**
Rs/kg	300	(Dezan Shira & Associates, 2023)
EUR/kg	336	
$/kg	5	(Sonal Gupta, Rupesh Kumar, Amit Kumar, 2024)
EUR/kg	4.68	
$/kg	6.44	(Hafiz Muhammad Uzair Ayub, Sabla Y. Alnouri, Mirko Stijepovic, Vladimir Stijepovic, Ibnelwaleed A. Hussein, 2024)
EUR/kg	6.03	
Rs/kg	419	Average - This study
EUR/kg	4.69	

Table 25 provides an overview of the sources and values used to estimate the CAPEX set in the Components- Solar tab.

Table 25: CAPEX Solar parameter sources; Source: Own creation

Case/Type	**Unit**	**Value**	**Source**
	Rs crore/MW	4.67	(Central Electricity Authority, 2023)
	Mil Eur/MW	0.52	
	USD/kW	590	(Raj Sawhney, John Hearn, Ross Hibbett, Khaya Kingston, Makenna Parkinson, Joseph Majkut, 2023)
	Mil Eur/MW	0.55	
	Mil Eur/MW	0.60	(Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023)

2020	Rs crore/MW	3.5	(Will Hall, 2020)
	Mil Eur/MW	0.39	
2050	Rs crore /kW	3	
	Mil Eur/MW	0.34	
Agrivoltaics overhead	Rs crore/MW	4.42	Commissioned projects in India
	Mil Eur/MW	0.49	
Agrivoltaics overhead	Rs crore/MW	5.04	
	Mil Eur/MW	0.56	
Agrivoltaics overhead	Rs crore/MW	4.64	
	Mil Eur/MW	0.52	
Agrivoltaics overhead	Rs crore/MW	6.00	
	Mil Eur/MW	0.67	
Agrivoltaics arable	Eur/kWp	1146.05	(Fraunhofer ISE, 2024)
Agrivoltaics permanent crops	Eur/kWp	983.11	
Interspace	Eur/kWp	800.05	
Increase in CAPEX with tracking	%	41.00	Fraunhofer ISE internal analysis
CAPEX fixed	Eur/kWp	550	(Nicolas Campion, Hossein Nami, Philip R. Swisher, Peter Vang Hendriksen, Marie Münster, 2023)
CAPEX 1 axis tracking	Eur/kWp	650	
Increase in CAPEX with tracking	%	18.18	
CAPEX ratio fixed		0.9	(Zabir Mahmud)
CAPEX ratio tracking		1.15	
Increase in CAPEX with tracking	%	27.78	
Average increase in CAPEX with tracking	%	26.39	Considered in this study

Table 26 provides an overview of the sources and values used to estimate the CAPEX set in the Components- Wind tab.

Table 26: CAPEX Wind parameter sources; Source: Own creation

Case/Type	Unit	Value	Source
	Rs crore/MW	6.16	(Central Electricity Authority, 2023)
	Mil Eur/MW	0.69	
	USD/kW	926	(Raj Sawhney, John Hearn, Ross Hibbett, Khaya Kingston, Makenna Parkinson, Joseph Majkut, 2023)
	Mil Eur/MW	0.87	
	Mil Eur/MW	1.20	(Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023)
2020	Rs crore/MW	3.7	(Will Hall, 2020)
	Mil Eur/MW	0.41	
2050	Rs crore /kW	3.2	
	Mil Eur/MW	0.36	

Table 27 provides an overview of the sources and values used to estimate the CAPEX set in the Components- Electrolyser tab.

Table 27: CAPEX Electrolyser parameter sources; Source: Own creation

Case/Type	Unit	Value	Source
PEM	Mil Eur/MW	0.75	(Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023)
PEM	USD/kW	599	(Takuma Otaki, 2023)
	Mil Eur/MW	0.56	
PEM	USD/kW	615	
	Mil Eur/MW	0.58	
Alkaline -2020	Rs crore/MW	6.66	(Will Hall, 2020)
	Mil Eur/MW	0.74	
2030	Rs crore/MW	2.96	
	Mil Eur/MW	0.33	
2050	Rs crore /kW	1.48	
	Mil Eur/MW	0.17	
PEM -2020	Rs /kW	8.14	
	Mil Eur/MW	0.91	
2030	Rs /kW	4.81	
	Mil Eur/MW	0.54	

2050	Rs /kW	1.48	
	Mil Eur/MW	0.17	
Overground steel tank storage	Eur/kg	500	(Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, 2023)
	USD/kg	240	(Miao Yang, Ralf Hunger, Stefano Berrettoni, Bernd Sprecher, Baodong Wang, 2023)
	Eur/kg	225	

Table 28 provides an overview of the sources and values used to estimate the CAPEX set in the Components- Battery and Inverter tab.

Table 28: CAPEX Battery and Inverter tab parameter sources; Source: Own creation

CAPEX	**Unit**	**Value**	**Source**
Battery			
2020	Rs cr/MWh	1.4	(Will Hall, 2020)
	Mil Eur/MWh	0.16	
2050	Rs cr/MWh	0.7	
	Mil Eur/MWh	0.08	
2020	Rs cr/MW	11	
2050	Rs cr/MW	8	
2020	$/kWh	206	(Dharik Sanchan Mallapragada, Emre Gencer, Patrick Insinger, David William Keith, Francis Martin O'Sullivan, 2020)
	Mil Eur/MWh	0.19	
2030	$/kWh	77	
	Mil Eur/MWh	0.07	
2020	$/kW	589	
2030	$/kW	477	
2020	$/kWh	203	(Deorah, Shruti M., Nikit Abhyankar, Siddharth Arora, Ashwin Gambhir, Amol A. Phadke, 2020)
	Mil Eur/MWh	0.19	
2025	$/kWh	134	
	Mil Eur/MWh	0.13	
2030	$/kWh	103	
	Mil Eur/MWh	0.10	
Inverter			
2020	$/kWh	16	

2025	$/kWh	13	(Deorah, Shruti M., Nikit Abhyankar, Siddharth Arora, Ashwin Gambhir, Amol A. Phadke, 2020)
2030	$/kWh	11	
2020	Mil Eur/MWh	0.015	
	Mil Eur/MW	0.060	
2025	Mil Eur/MWh	0.012	
	Mil Eur/MW	0.049	
2030	Mil Eur/MWh	0.010	
	Mil Eur/MW	0.041	
2019	Rs/W	2.14	(Eero Vartiainen, Gaëtan Masson, Christian Breyer, David Moser, Eduardo Román Medina, 2020)
	Mil Eur/MW	0.024	

Table 29 provides an overview of the sources and values used to estimate the extra revenue set in the financial data tab.

Table 29: Extra revenue tariff sources; Source: Own creation

Parameter	**Unit**	**Value**	**Source**
First 50 units non below poverty line consumer	Rs/kWh	0.265	(Paschim Gujarat Vij Company Limited, 2024)
Next 50 units	Rs/kWh	0.31	
Next 150 units	Rs/kWh	0.375	
Above 250 units	Rs/kWh	0.49	
First 50 units below poverty line consumer	Rs/kWh	0.15	
Average	Rs/kWh	0.318	
Green tariff	Rs/kWh	1	
Total	Rs/kWh	1.318	
	Eur/kWh	0.015	

Table 30 provides an overview of the sources and values used to estimate scaling factors set in the sensitivity analysis tab.

Table 30: Sensitivity analysis scaling factor sources; Source: Own creation

Year	**Unit**	**Solar**	**Wind**	**Electrolyser**	**Source**
2020	$/kW	690	1040	700	(Jacob L.L.C.C. Janssen, Marcel Weeda, Remko J. Detz, Bob van der Zwaan, 2022)
	Eur/kW	646	973	655	
2030	$/kW	450	960	600	
	Eur/kW	421	898	561	
2040	$/kW	370	920	520	
	Eur/kW	346	861	487	
2050	$/kW	320	890	450	
	Eur/kW	299	833	421	
2011	$/kW	2584			(Florian Egli, Nikolai Orgland, Michael Taylor, Tobias S. Schmidt, Bjarne Steffen, 2023)
	Eur/kW	2418			
2012	$/kW	1848			
	Eur/kW	1729			
2013	$/kW	2028			
	Eur/kW	1898			
2014	$/kW	1085			
	Eur/kW	1015			
2015	$/kW	987			
	Eur/kW	924			
2016	$/kW	884			
	Eur/kW	827			
2017	$/kW	760			
	Eur/kW	711			
2018	$/kW	595			
	Eur/kW	557			
2019	$/kW	862			
	Eur/kW	807			
2020	$/kW	580	1040		(IEA, 2022)
	Eur/kW	543	973		
2030	$/kW	310	980		

	Eur/kW	290	917		
2050	$/kW	320	940		
	Eur/kW	299	880		

Table 31 provides an overview of the sources and values used to estimate scaling factor for battery set in the sensitivity analysis tab.

Table 31: Battery sensitivity analysis scaling factor sources; Source: Own creation

Year	**Battery CAPEX (Eur/kWh)**	**Source**
2017	376	(IEA, 2022), (Eero Vartiainen, Gaëtan Masson, Christian Breyer, David Moser, Eduardo Román Medina, 2020)
2018	308	
2019	275	
2020	251	
2021	229	
2022	209	
2023	192	
2024	176	
2025	207	
2026	151	
2027	141	
2028	132	
2029	124	
2030	172	
2031	112	
2032	106	
2033	102	
2034	98	
2035	154	
2036	91	
2037	88	
2038	85	
2039	82	
2040	142	

2041	78	
2042	76	
2043	74	
2044	73	
2045	71	
2046	70	
2047	69	
2048	67	
2049	66	
2050	65	

Figure 27 shows the equation used for calculating the scaling factors for sensitivity analysis of Solar.

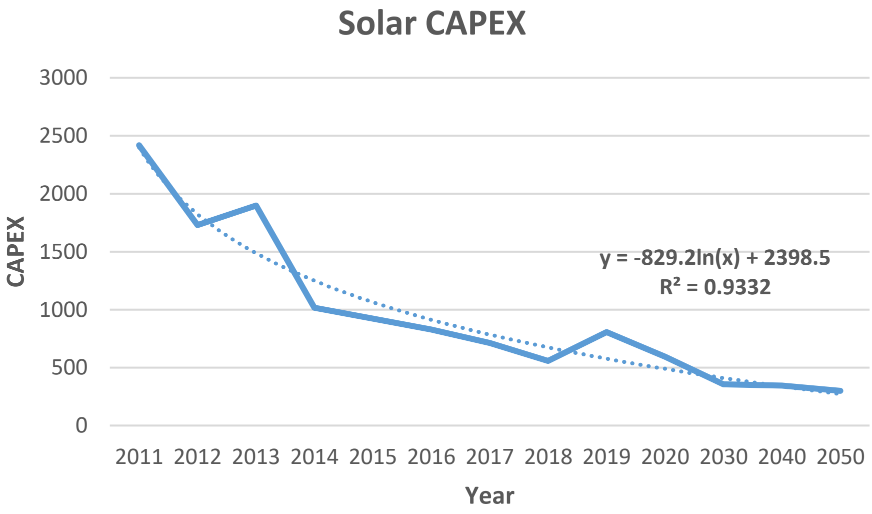

Figure 27: Graph and trendline for sensitivity analysis for scaling factor of Solar; Source: Own creation

Figure 28 shows the equation used for calculating the scaling factors for sensitivity analysis of Wind.

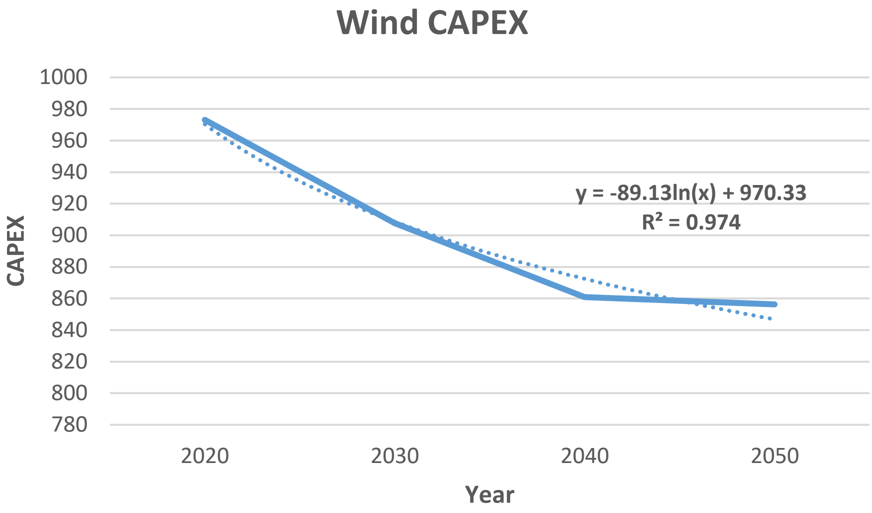

Figure 28: Graph and trendline for sensitivity analysis for scaling factor of Wind; Source: Own creation

Figure 29 shows the equation used for calculating the scaling factors for sensitivity analysis of the electrolyser.

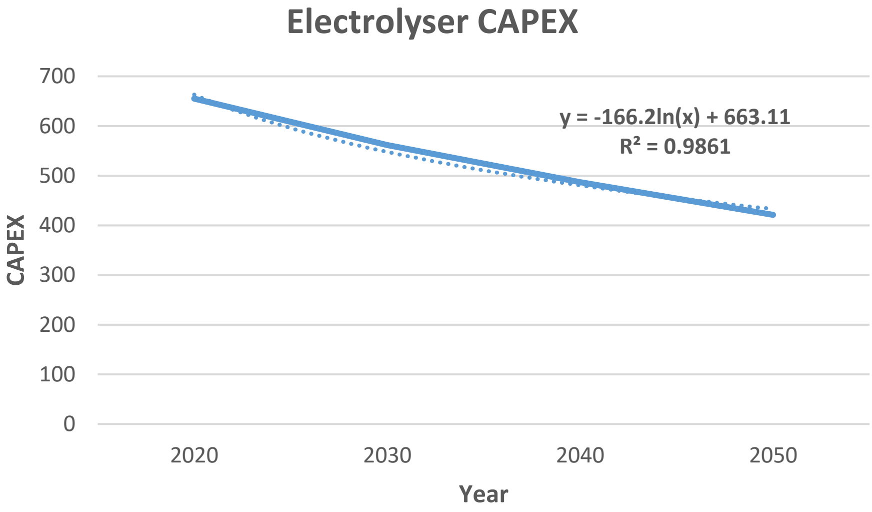

Figure 29: Graph and trendline for sensitivity analysis for scaling factor of electrolyser; Source: Own creation

Figure 30 shows the equation used for calculating the scaling factors for sensitivity analysis of the Battery.

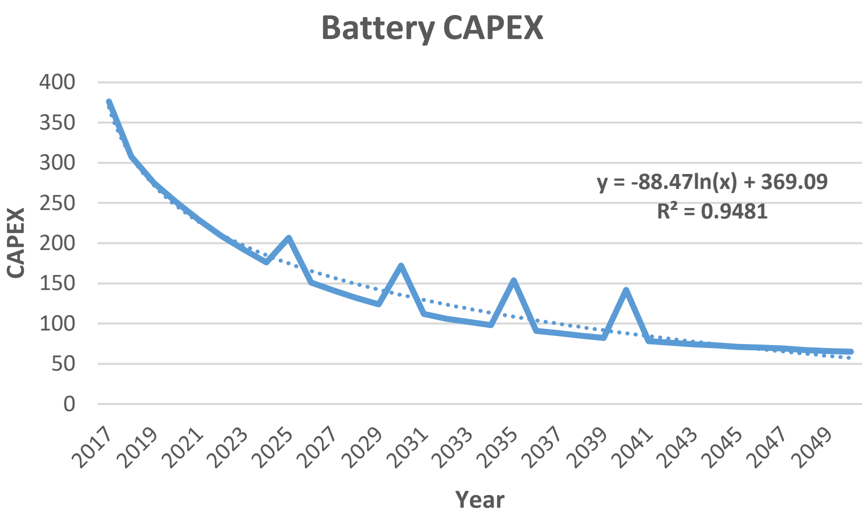

Figure 30: Graph and trendline for sensitivity analysis for scaling factor of Battery; Source: Own creation

Table 32 provides an overview of the scaling factors set in the sensitivity analysis tab.

Table 32: Sensitivity analysis scaling factors; Source: Own creation

Parameter	**Year**		
	2024	2040	2050
Solar			
CAPEX (Eur/kW)	457	338	272
Factor	1	0.74	0.59
Wind			
CAPEX (Eur/kW)	940	872	847
Factor	1	0.93	0.90
Electrolyser			
CAPEX (Eur/kW)	607	481	433
Factor	1	0.79	0.71
Battery			
CAPEX (Eur/kW)	185	88	57
Factor	1	0.47	0.31

Figures below show the graphs used in section 4.3.1.1 for all system configurations.

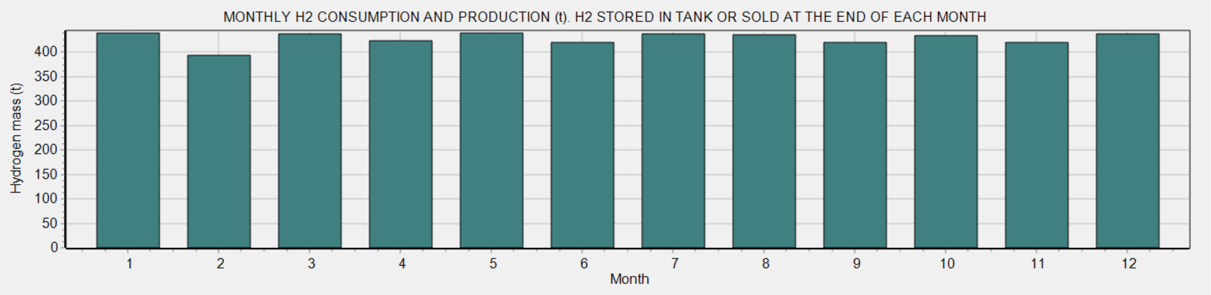

Figure 31: Monthly hydrogen production for arable farming grid system configuration; Source: MHOGA software snapshot

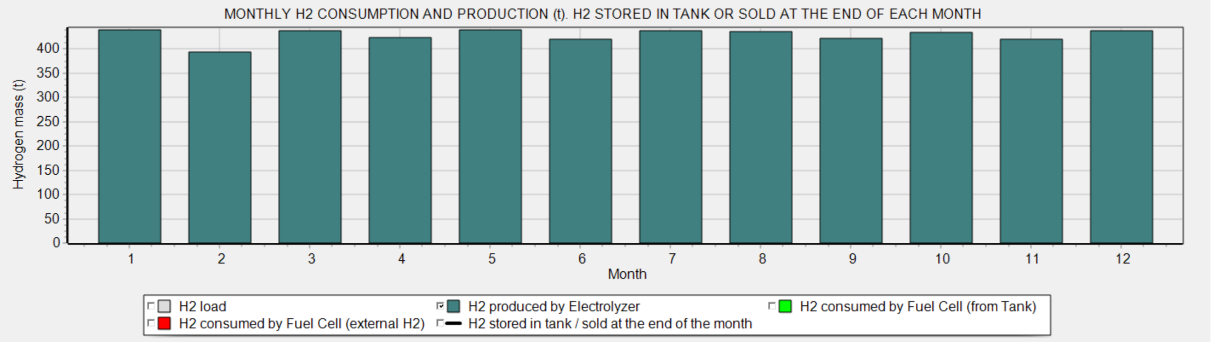

Figure 32: Monthly hydrogen production for permanent crops grid system configuration; Source: MHOGA software snapshot

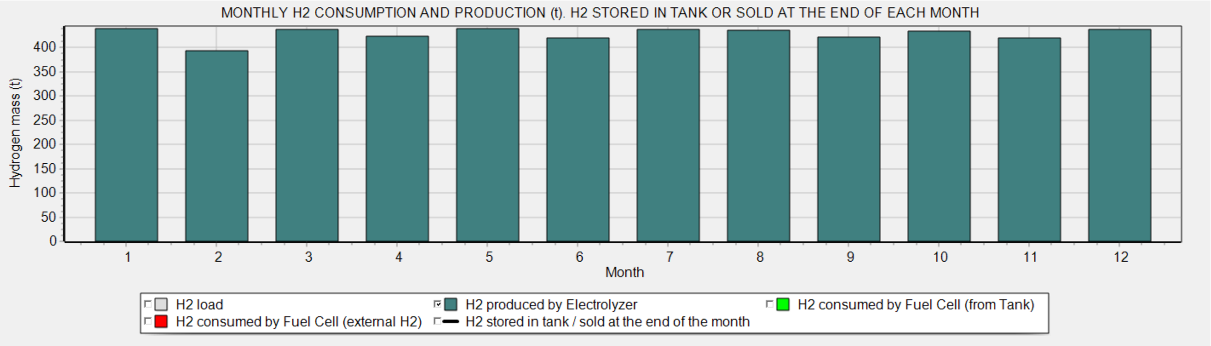

Figure 33: Monthly hydrogen production for overhead dynamic grid system configuration; Source: MHOGA software snapshot

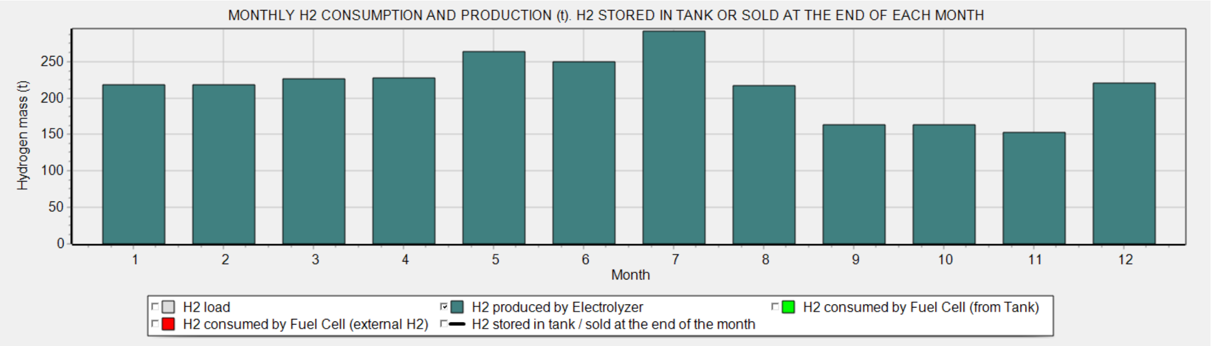

Figure 34: Monthly hydrogen production for permanent crops green + grid to sell system configuration; Source: MHOGA software snapshot

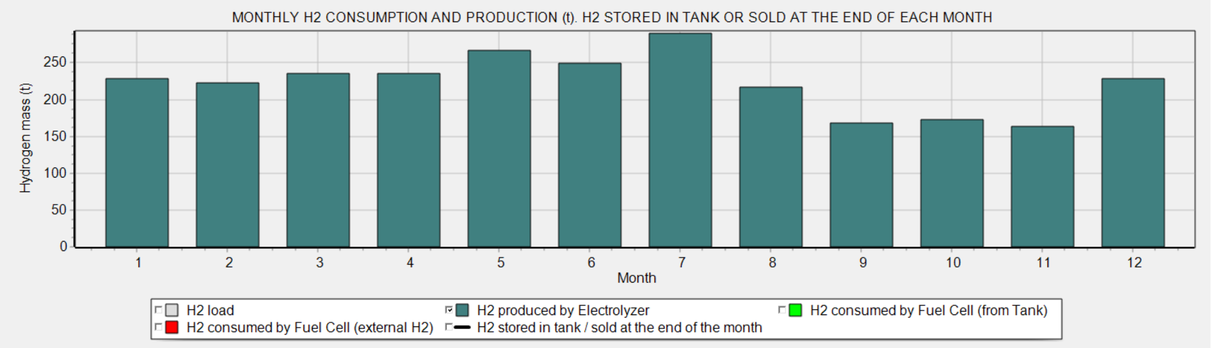

Figure 35: Monthly hydrogen production for overhead dynamic green + grid to sell system configuration; Source: MHOGA software snapshot

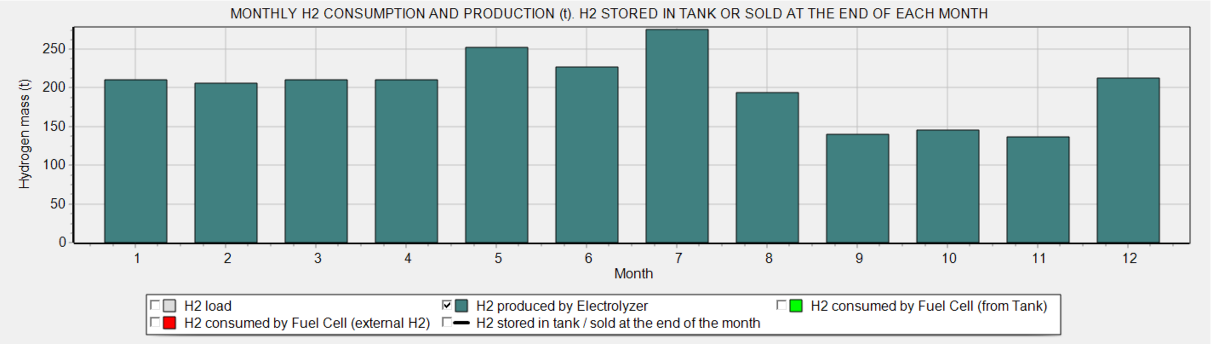

Figure 36: Monthly hydrogen production for arable farming green off-grid system configuration; Source: MHOGA software snapshot

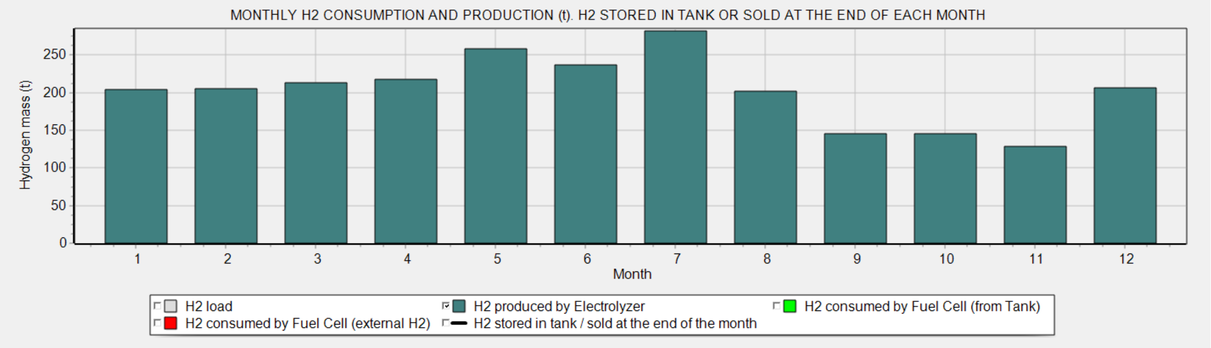

Figure 37: Monthly hydrogen production for permanent crops green off-grid system configuration; Source: MHOGA software snapshot

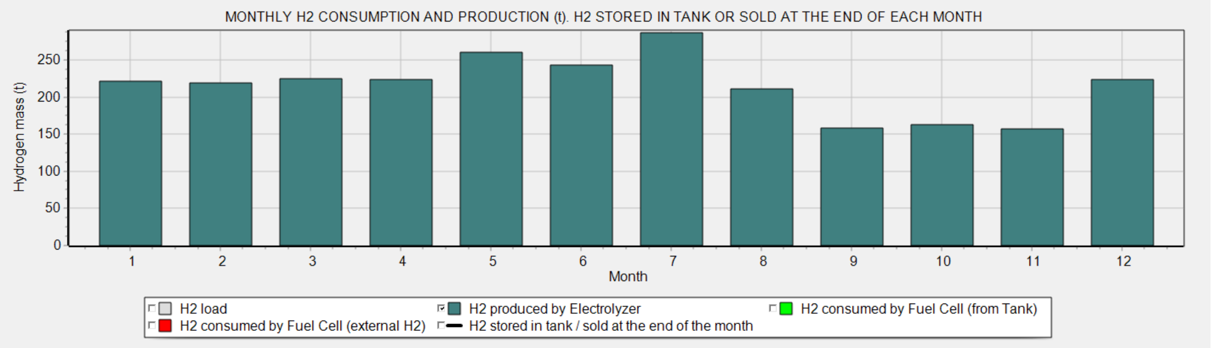

Figure 38: Monthly hydrogen production for interspace vertical green off-grid system configuration; Source: MHOGA software snapshot

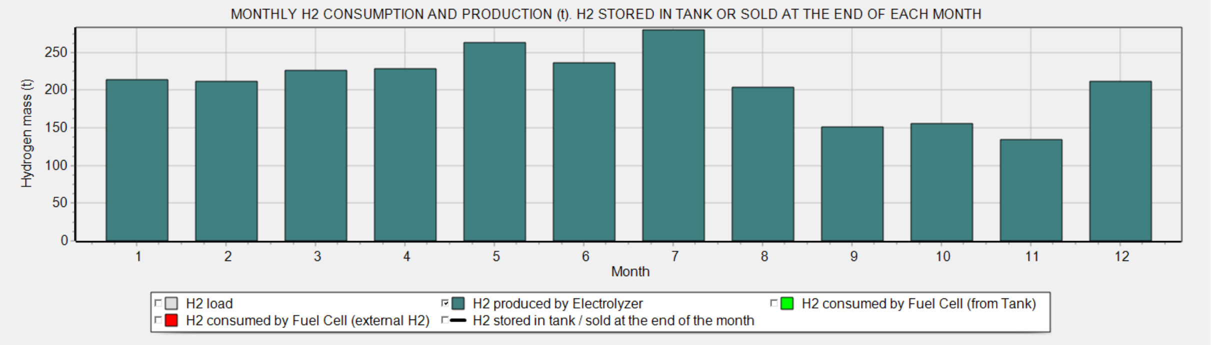

Figure 39: Monthly hydrogen production for overhead dynamic green off-grid system configuration; Source: MHOGA software snapshot

Figures below show the graphs used in section 4.3.1.2 for all system configurations.

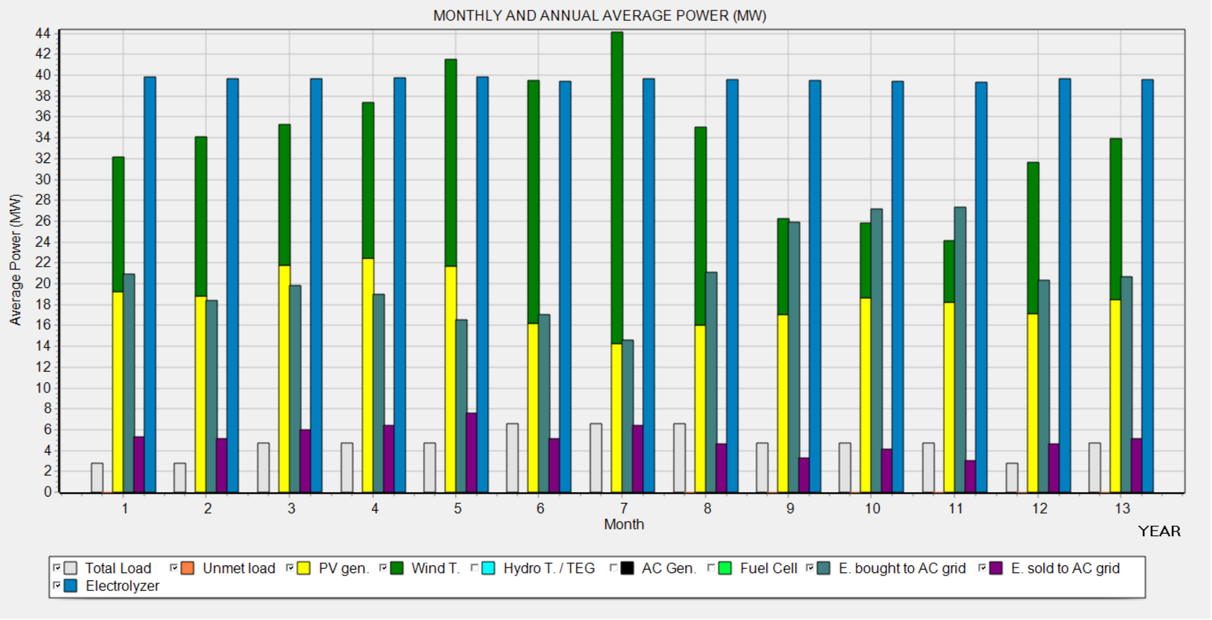

Figure 40: Monthly and annual average power for arable farming grid system configuration; Source: MHOGA software snapshot

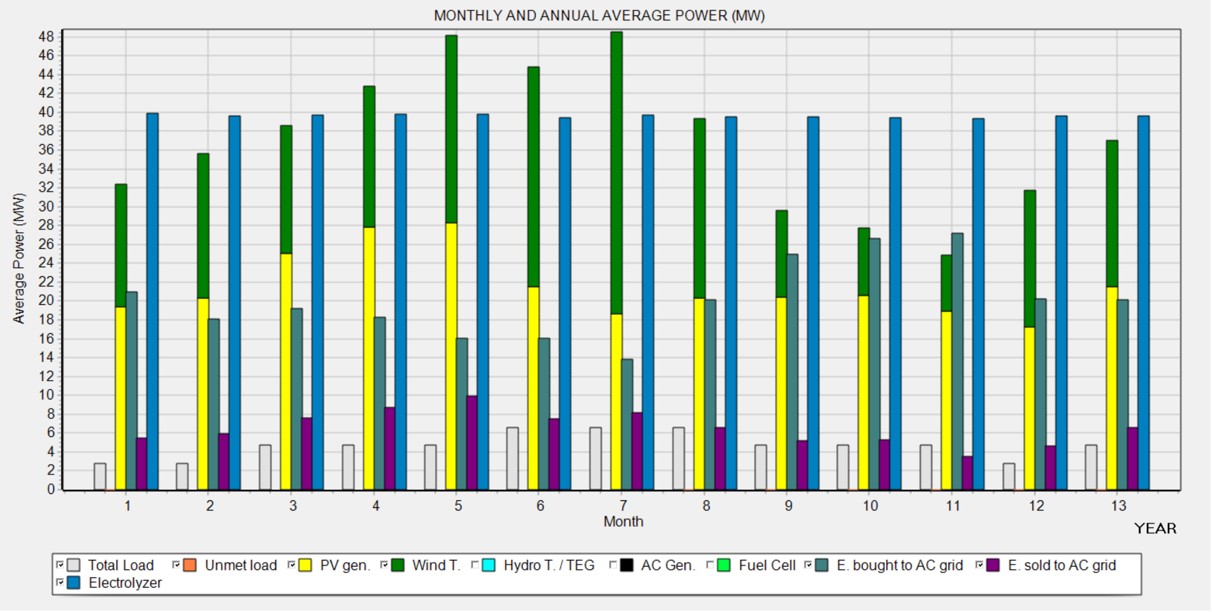

Figure 41: Monthly and annual average power for permanent crops grid system configuration; Source: MHOGA software snapshot

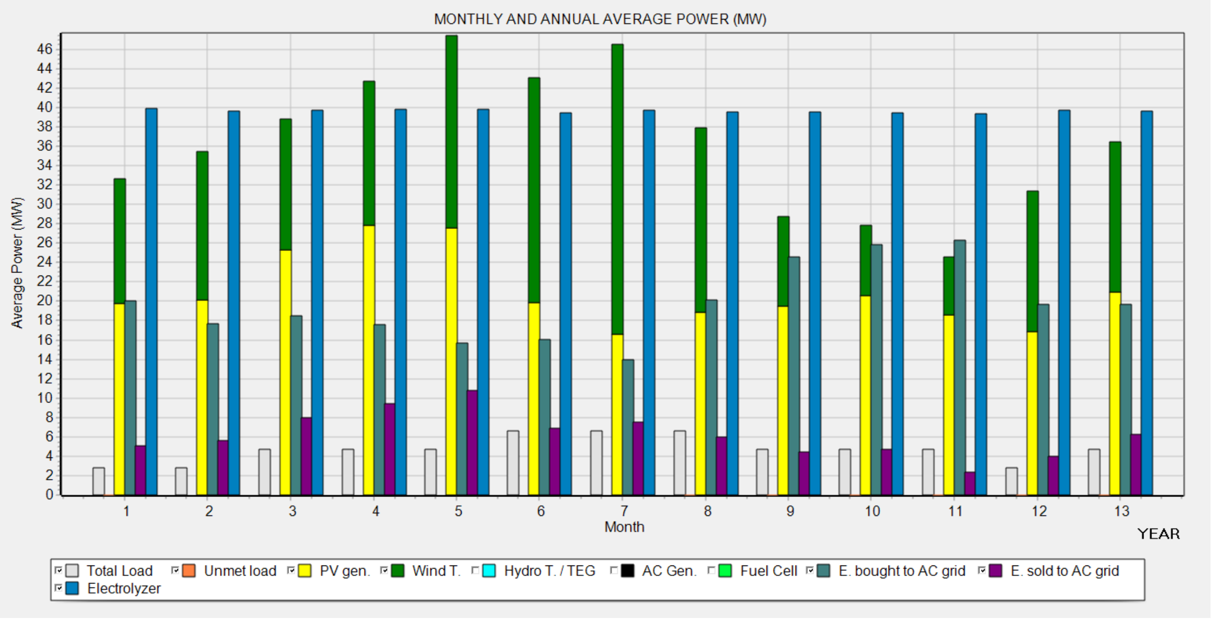

Figure 42: Monthly and annual average power for overhead dynamic grid system configuration; Source: MHOGA software snapshot

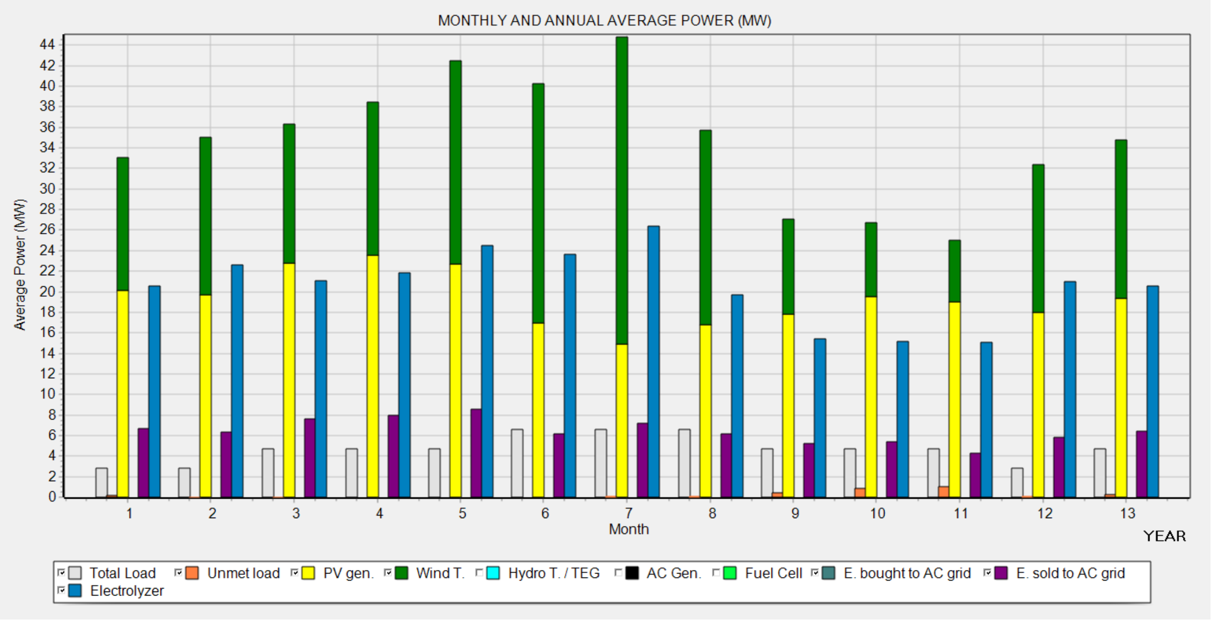

Figure 43: Monthly and annual average power for arable farming green + grid to sell system configuration; Source: MHOGA software snapshot

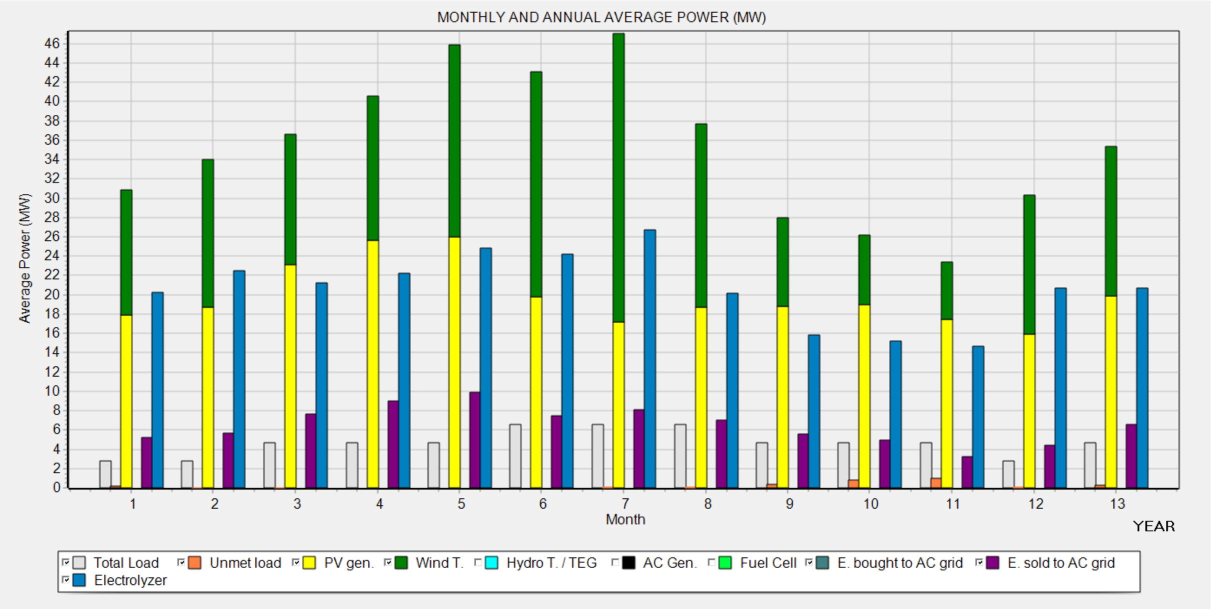

Figure 44: Monthly and annual average power for permanent crops green + grid to sell system configuration; Source: MHOGA software snapshot

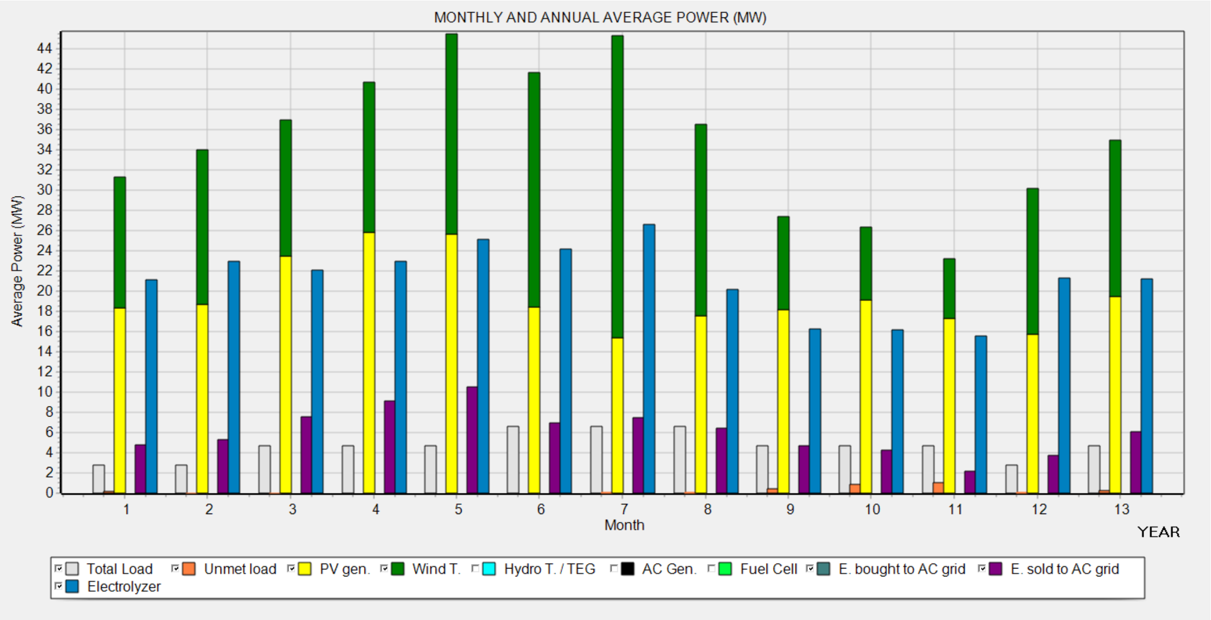

Figure 45: Monthly and annual average power for overhead dynamic green + grid to sell system configuration; Source: MHOGA software snapshot

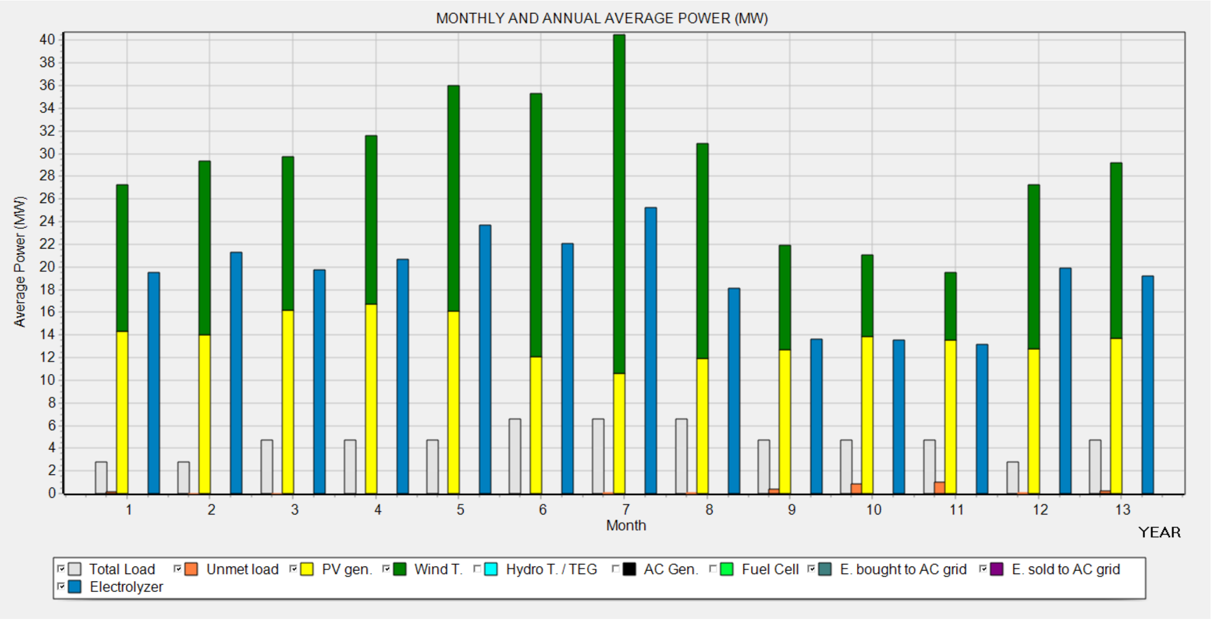

Figure 46: Monthly and annual average power for arable farming green off grid system configuration; Source: MHOGA software snapshot

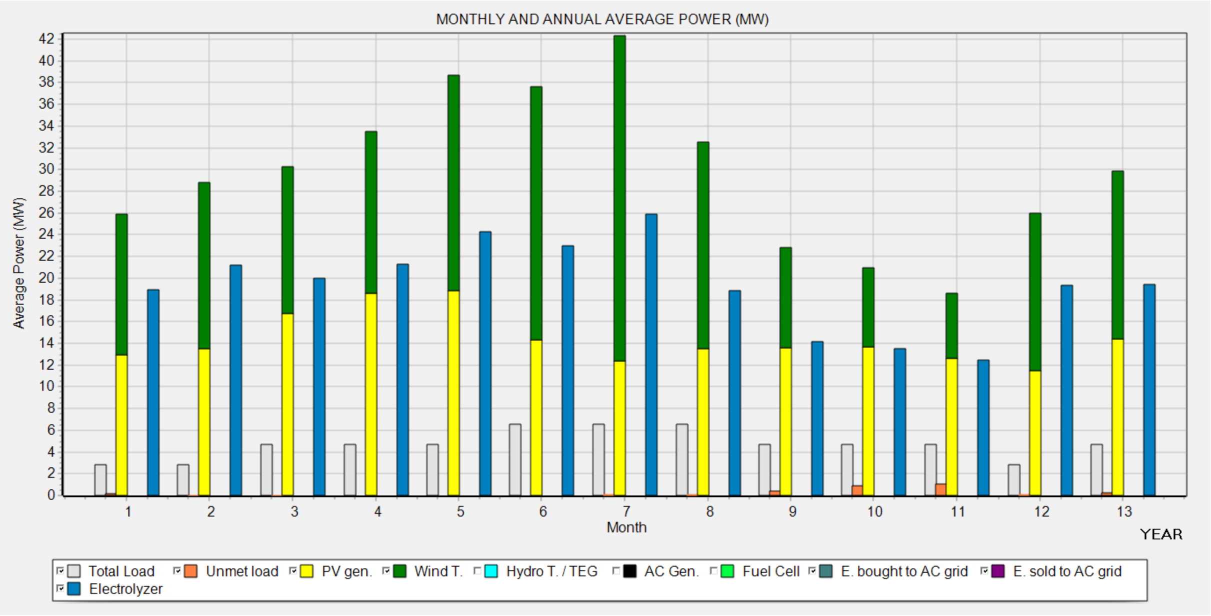

Figure 47: Monthly and annual average power for permanent crops green off grid system configuration; Source: MHOGA software snapshot

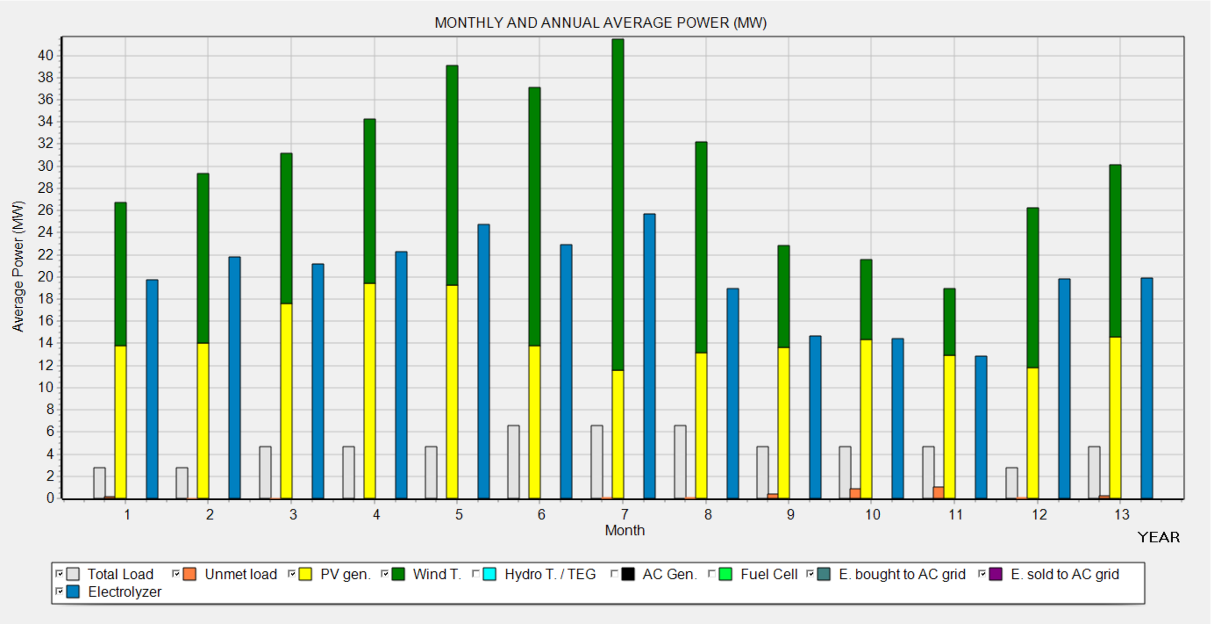

Figure 48: Monthly and annual average power for overhead dynamic green off grid system configuration; Source: MHOGA software snapshot

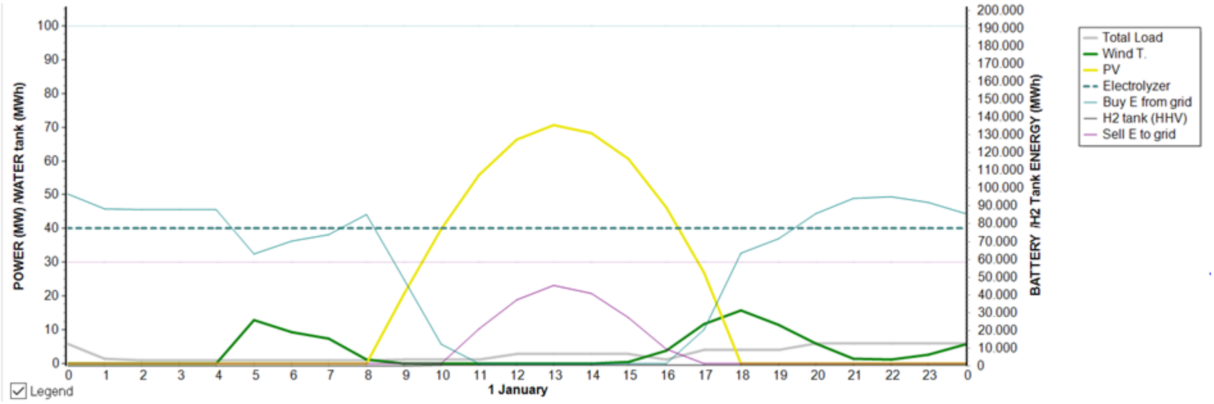

Figure 49: Hourly profile for arable farming grid system configuration: Source: MHOGA software snapshot

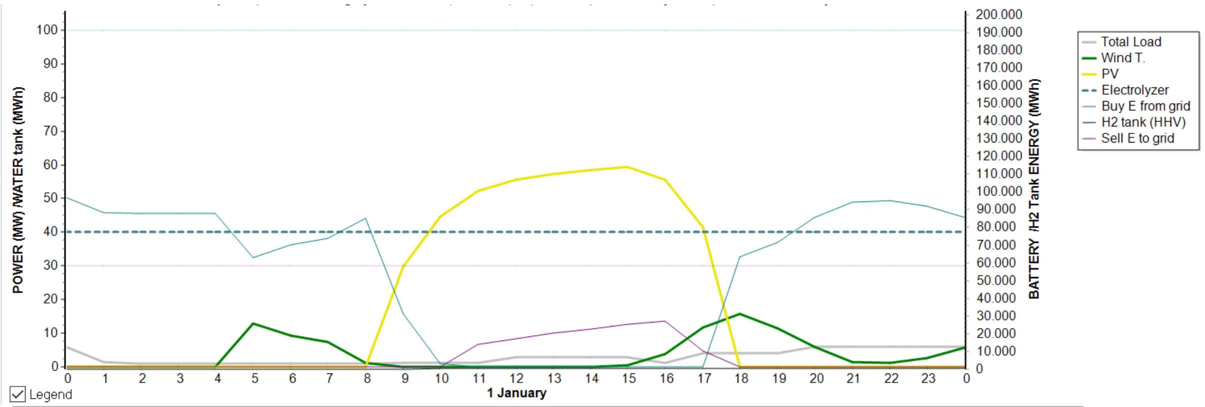

Figure 50: Hourly profile for overhead dynamic grid system configuration: Source: MHOGA software snapshot

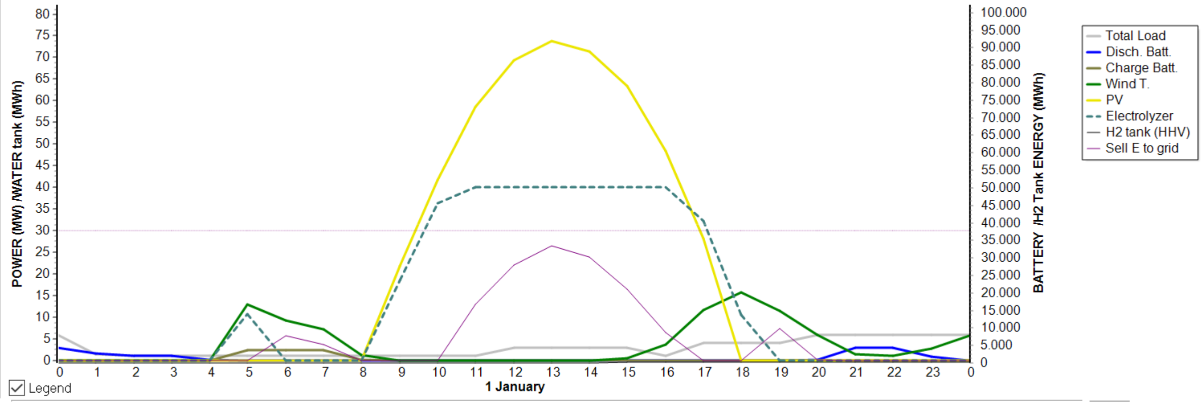

Figure 51: Hourly profile for arable farming green + grid to sell system configuration: Source: MHOGA software snapshot

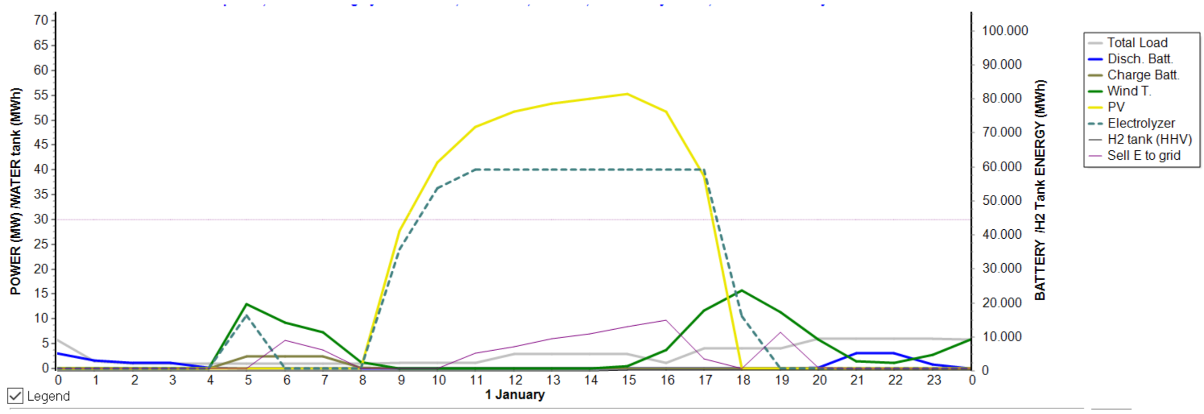

Figure 52: Hourly profile for overhead dynamic green + grid to sell system configuration: Source: MHOGA software snapshot

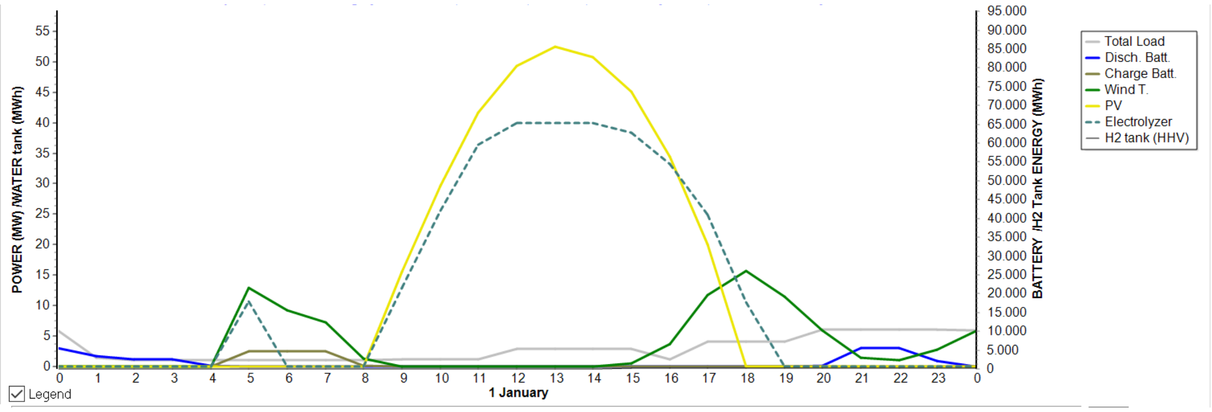

Figure 53: Hourly profile for arable farming green off-grid system configuration: Source: MHOGA software snapshot

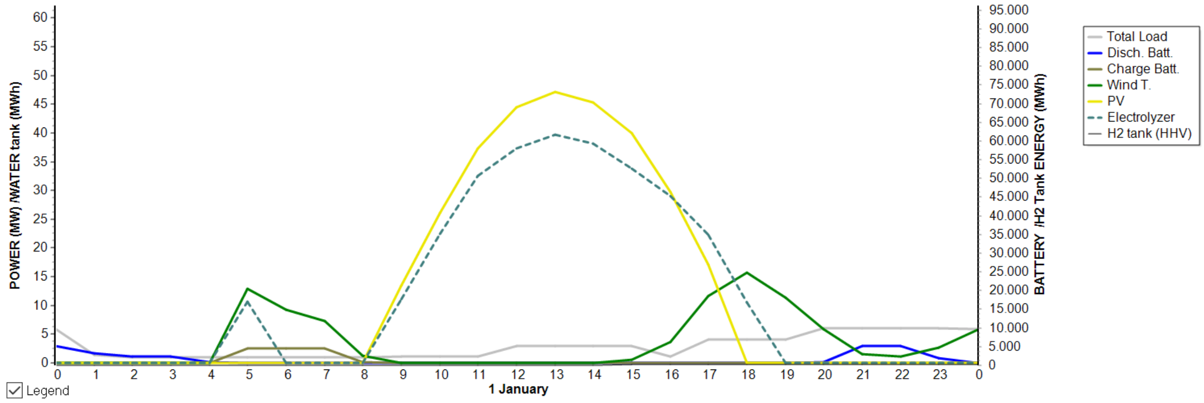

Figure 54: Hourly profile for permanent crops green off-grid system configuration: Source: MHOGA software snapshot

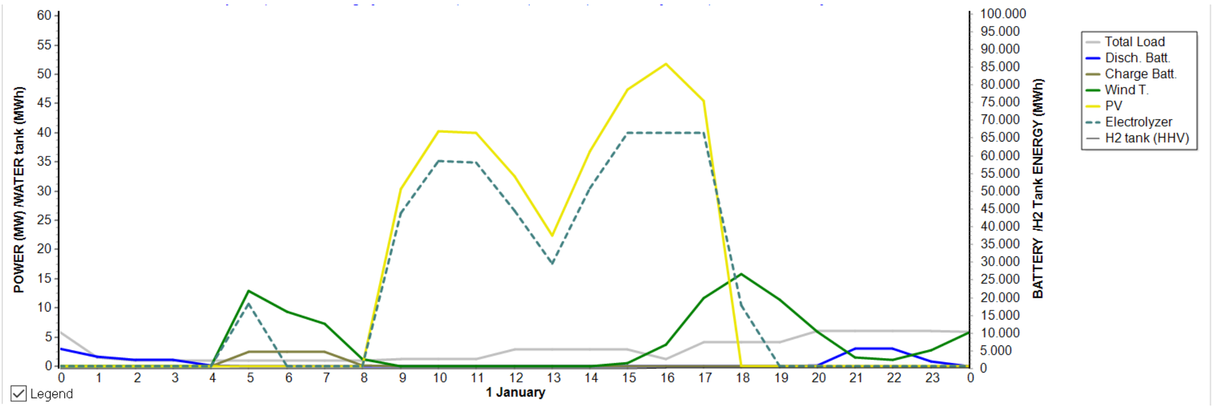

Figure 55: Hourly profile for interspace vertical green off-grid system configuration: Source: MHOGA software snapshot

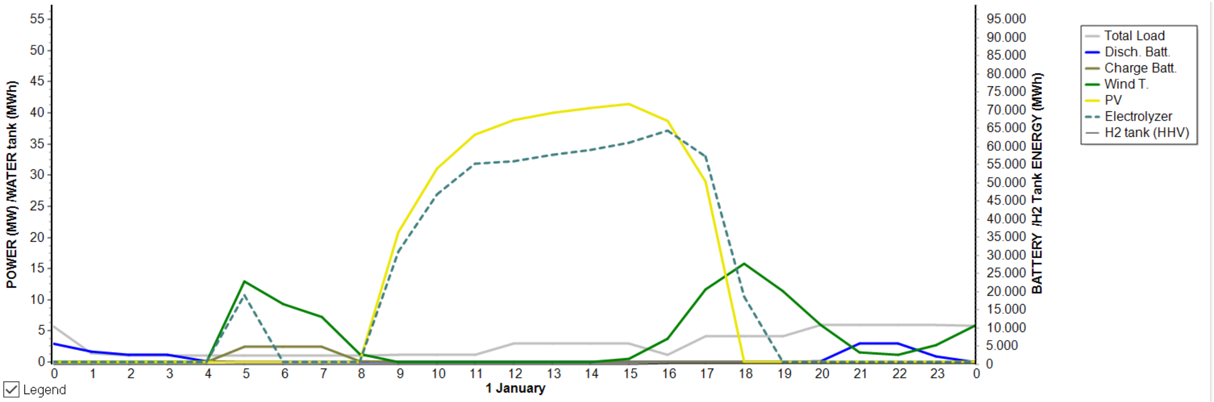

Figure 56: Hourly profile for overhead dynamic green off-grid system configuration: Source: MHOGA software snapshot

Declaration of authenticity

I hereby assure that I have completed the present master thesis with the title:

‘Development and analysis of cost optimized system scenarios for hydrogen production with agrivoltaics and wind energy in India.’

independently and only with the aids indicated. All passages that I have taken from literature or from other sources such as Internet pages I have clearly identified as quotations with indication of the source.

31.07.2024, Hamburg
Date, Place

Sign