D7.1 Energy generation and utilization analysis for the existing demonstrators

Symbiosyst

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In this work, artificial intelligence has been used for the gathering of background information on country-specific regulations and to identify reference documents (mainly MS Copilot), as well as support in scripting. Suggestions for phrasing the respective text have been used in some cases.

Executive Summary

The SYMBIOSYST project, supported by the EC Horizon Europe Programme, aims to bridge the gap between solar energy production and agriculture by developing tailored photovoltaic (PV) solutions for both greenhouse and open-field agriculture across diverse climatic conditions in three nations. The initiative includes the creation of several agri-PV demonstrators, encompassing scenarios from vegetable farming to fruit cultivation with traditional and other training systems under adjustable tracking systems or into greenhouses with roof partially covered by PV modules. In particular the agri-PV demonstrators are:

- Bolzano (Italy) with an open apple orchard combined with a PV tracking system that partially covers the apple trees
- Scalea (Italy) with an open citrus fruit production, with existing PV systems (this is also a demo driver).
- Barcelona (Spain) with an open cultivation of short-stature and trellised seasonal vegetables such as tomatoes, onions, lettuce, and fava beans.
- Mons (Belgium) with a greenhouse for a.o. tomatoes with an existing PV system and an on-site restaurant. Note that this system is replacing another one that is described in earlier Deliverables.

In this study, we are investigating both the positive energy impact and the financial viability of agri-PV systems at these sites in combination with different uses of the generated energy, forming specific use cases. The analysis is based on the input of various partners as well as a literature study to map key boundary conditions. It includes nearby facilities as the headquarters of our partner SBB, a fruit cooperative in the Bolzano area and energy communities both in Italy and Spain. On-farm consumption, in particular irrigation, is taken into account, and profiles of different farms are analysed for the three open-agri-PV sites. Sizing studies based on parametric optimisation are conducted for the different cases, and financial results and their dependence on scaling are discussed. Given that the agri-PV business is trending from moderately sized on-farm systems to investment cases, larger sizes are being considered. We are comparing the results to the recent tender in Italy and are finding that the systems of this project would fare favourably under these conditions.

For agri-PV to be viable, sources of remuneration beyond grid injection at market price are required. These can be a feed-in tariff, investment subsidies (as provided by the recent Italian recovery program), or contracts with users through energy communities (ECs) or power purchase agreements (PPAs). This study shows illustrative cases for each. It concludes that the self-consumption and grid-feed cases are only viable with sufficient subsidies, as they used to be given in Italy, but not in Spain. The combinations with nearby consumers all realistically yield financially viable cases if the premium for energy exchange is sufficiently high.

While the sizing optimisation of PV systems trends towards larger systems, battery storage was investigated to enhance self-supply and revenues but not found to be effective except in case of an energy community in Spain. However, the financial outcome is marginal, and small changes in pricing and boundary conditions could alter the relation. Generally speaking, the present study is based on a range of assumptions, of which we can but try to solidify them. Arguably, it is positioned somewhat on the optimistic side in order not to disqualify potential use cases prematurely. As should be clear from the ongoing changes in energy markets and regulatory and financial boundary conditions, it can only present a snapshot in time.

Table of Contents

Table of Contents **5**

1. Introduction **9**

1.1. Description of the Deliverable Contents *9*

1.2. Boundary Conditions *10*

1.3. Document structure *11*

1.4. Reference Material *11*

2. Methodology **12**

2.1. Approach to Use Cases *12*

2.2. Performance Indicators *13*

2.2.1. Energy use 13

2.2.2. Net Present Value 13

2.2.3. Return on Investment (ROI) 13

2.2.4. Levelized Cost of Electricity (LCOE) 13

2.2.5. Pay-back Period (PBP) 14

2.3. Cash Flow Spreadsheet *14*

2.4. Optimisation Model for Energy Flows and Costs *14*

2.4.1. Input data 14

2.4.2. Optimisation Goals 15

2.5. Use Case Selection *16*

2.6. PV Generation Modelling *16*

2.7. Consumption Profiles of the Project *17*

2.7.1. SBB Headquarters 17

2.7.2. Fruit Cooperative 18

2.7.3. Bolzano Energy Community 19

2.7.4. Consumption modelling (citrus farm) 20

2.7.5. Electric tractors 21

2.7.6. Robots and precision tools 22

3. External Data Collection and Sources **23**

3.1. Electricity market and CO_2 intensity *23*

3.2. Cost parameters *23*

3.2.1. Basic cost categories 23

3.2.2. Operating expenditure 24

3.2.3. Costs of capital 25

3.2.4. Mounting structures 25

3.2.5. Geographical considerations and electrical system 25

3.2.6. Inverters 26
3.2.7. Storage systems 26
3.3. Country Specifics – Italy *27*
3.3.1. Grid withdrawal 27
3.3.2. Grid Injection 27
3.3.3. Energy Communities 28
3.3.4. Investment subsidies and feed-in tariffs 29
3.4. Country Specifics – Spain *30*
3.4.1. Grid withdrawal 30
3.4.2. Grid Injection 30
3.4.3. Energy Communities – Legislation 30
3.4.4. Energy Communities – Test Case 31
3.4.5. Power purchase agreements 31
3.4.6. Investment subsidies and feed-in tariffs 32
3.4.7. Situation of agri-PV 32
4. Results and Analysis **34**
4.1. Load Profiles and Consumption Patterns of the Use Cases *34*
4.2. Open Agri-PV - Bolzano Apple Orchard *34*
4.2.1. On-farm Consumption / FIT 35
4.2.2. Beyond the Farm: Fruit Cooperative 37
4.2.3. Energy Community 38
4.2.4. Headquarters of SBB 39
4.3. Open Agri-PV - Scalea Citrus Orchard *40*
4.4. Open Agri-PV - Barcelona Lettuce Farm *41*
4.4.1. On-farm consumption 42
4.4.2. Agri-PV with Local Energy Community 43
4.5. Closed Agri-PV – Mons, Belgium *45*
4.6. Italian tender as reference *45*
4.7. Summary and Discussion of Results *46*
4.8. Key Dependencies *48*
5. Conclusions and Recommendations **48**
References **50**

Index of Figures

Figure 1: Parameters and treatment steps of the optimisation study..... 15

Figure 2: Hourly consumption data of the SBB headquarters for the year 2025. The insert shows the third week of April. 17

Figure 3: Hourly net grid withdrawal of the Frubona cooperative during the year 2025. Insets show the second halves of April and September, respectively. 18

Figure 4: Monthly totals of electricity consumption for the three groups of consumers. 19

Figure 5: Hourly consumption profiles for a representative week in March, per group. 20

Figure 6: Inverter price as a function of nominal power for PV-only and hybrid devices. Basis are wholesale prices with a 25% markup. 26

Figure 7: Price of storage systems as a function of the usable capacity. 27

Figure 8: Annual consumption profile with hourly averages for a set of 1 000 Spanish households. The inset shows data from the first two weeks of April as an example. 32

Figure 9: Top: Discounted ROI as a function of rated power of the PV system for the Bolzano farm with self-consumption and FIT. Bottom: NPV as a function of the CAPEX for the same dataset. The colour of the symbols indicates the IRR (darker = better) while their size indicates the battery capacity. 37

Figure 10: NPV for the Bolzano fruit cooperative as a function of CAPEX. The colour of the symbols indicates the IRR (darker = better) while their size indicates the battery capacity. 38

Figure 11: dROI as a function of PV system size for the combination of agri-PV farm with the headquarters. 40

Figure 12: NPV for the Barcelona energy community with investment subsidies as a function of CAPEX. The colour of the symbols indicates the IRR (darker = better) while their size indicates the battery capacity. 45

Figure 13: Time profiles of generation, purchase and consumption for the Mons site for the period March 2025 to May 2026. 46

Index of Tables

Table 1: Overview of use cases related to each pilot installation 16

Table 2: Constituents and total consumption of the Bolzano energy community 19

Table 3: Assumptions for time profiles of main consumers in the citrus orchard 21

Table 4: Comparison of cost assumptions with Schindele et al. [15] 24

Table 5: Cost parameters for solar trackers used in the demonstrator systems 25

Table 6: Remuneration of energy shared in energy communities in Italy. ‘Pz’ is the hourly zonal market price. 28

Table 7: CAPEX and OPEX costs for the Bolzano system 35

Table 8: Parameters of the optimisation study for the Bolzano system, on-farm self-consumption and combined with a fruit cooperative and an energy community, with and without subsidy. 36

Table 9: Parameters for the optimisation of an orchard farm with the SBB headquarters as energy consumer 39

Table 10: CAPEX and OPEX costs for the Scalea system..... 41

Table 11: Parameters of the optimisation study for the Scalea system, on-farm self-consumption with FIT without subsidy and with the combination of CAPEX subsidy and fixed-price PPA. 42

Table 12: CAPEX and OPEX costs for the Barcelona system..... 43

Table 13: Parameters of the optimisation study for the Barcelona system, on-farm consumption and grid injection and combined with an energy community, with and without subsidy..... 44

Table 14: Schematic overview of results of the asset sizing study. 47

List of Abbreviations

Acronym	Meaning
Agri-PV	Agrivoltaics
CAP	Common Agricultural Policy (EU)
CAPEX	Capital Expenditure
CoO	Cost of Ownership
EC	Energy Community
ESCO	Energy Service Company
FIT	Feed-In Tariff
GCR	Ground coverage ratio
GHG	Greenhouse Gases
GWP	Global Warming Potential
HSAT	Horizontal Single-Axis Tracker
IRR	Internal Rate of Return
KPI	Key Performance Indicator
LACE	Levelized Avoided Cost of Energy
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Electricity
LEC	Local Energy Community
LER	Land Equivalent Ratio
NPV	Net Present Value
OPEX	Operational Expenditure
PNRR	Piano Nazionale di Ripresa e Resilienza (Italy: National Recovery and Resilience funds)
POA	Plane of Array
PPA	Power Purchase Agreement
PV	Photovoltaics
PZO	Prezzi Zonali Orari (Italy: hourly zonal market price)
(d)ROI	(discounted) Return On Investment
SME	Small and Medium-sized Enterprises
SOC	State of Charge (battery)
TCEC	Tariffa Premio per l'Energia Condivisa (Italy: premium for shared energy)
ToU	Time of Use
WACC	Weighted Annual Cost of Capital

1. Introduction

1.1. Description of the Deliverable Contents

The aim of the work in Task 7.1 leading to this Deliverable is to develop use case scenarios based on the systems demonstrated in the project, namely, apple orchards in Bolzano (Italy), citrus farms in Scalea (Italy), lettuce farms in Barcelona (Spain) and greenhouses in Mons (Belgium). To investigate their viability through a sizing study and cost/benefit analysis, the photovoltaic energy generation potential of each is aligned with consumption profiles of typical farms as they are, including the investigation of battery storage, and considering potential changes like the introduction of electric vehicles. Going beyond the farms, the exchange of energy with nearby facilities and energy communities is studied. Grid pricing for withdrawal and sales, and potential sales through power purchase agreements are considered as well.

The present analysis aims to generalise the results of the pilot installations for use in comparable farms. I.e., the goal is to answer the question “How can a farmer in a similar setting, characterized by geography, type of crops and typical farm size, valorise the PV-generated energy in an effective manner?” This entails also uses through specific contracting which yield better returns than mere grid injection. The use of battery storage is considered as an effective means to match supply and demand, and appropriate combined sizing of PV system and battery is studied through a variation analysis. Generally speaking, the energy consumption of the farm types relevant here is small, such that covering on-farm consumption does not require any sizeable agri-PV system. The report contains specific examples where the local setting provides the opportunity for extended energy use. Beyond that, abstractions of general regulations and boundary conditions are made to come to conclusions in general regarding the viability of a type of installation. This entails some simplifications which allow comparability. This Deliverable does not address any economic effects on the crop side, positive or negative, or secondary effects like water conservation. A more comprehensive overview including these will be provided in the upcoming Deliverable 7.2.

In this study, we are considering agri-PV investment projects as they may be realized by farmers that can install such systems in a similar way as the pilot installations of SYMBIOSYST. While we are using example cases with real systems, the generalisation that is required in order to show relevance to a larger range of farms requires an abstraction from the very specific settings of each case. This report should thus not be read as an advice how to design an agri-PV system for a specific farm, or as a statement that a specific combination of installation and use case is, or is not, profitable. Variables in each parameter both on the generation and cost side can lead to vastly different financial outcomes. Constraints on permitting, tendering and grid connection are weighing in as well. The situation is made even more complex by market variability and the limited predictability of future market conditions, especially given that there is increasingly an oversupply of grid electricity on sunny days, and that the roll-out of grid-level storage has only just begun. Further to that, taxation can vary dependent on the regulations and the business model chosen. The analysis is intentionally somewhat optimistic in order to not disqualify potential use cases prematurely.

Within Task 7.1 of the project, KUL and EURAC conducted the economic analysis, with the sizing study performed based on earlier work of KUL. ENGIE-LAB provided the system scaling data and market background. SBB gathered and analysed data of various farms as well as their organisation’s headquarters and local fruit cooperative, as well as market data for Italy. LUCISUN simulated the performance of the PV systems and provided year-around time profiles of generated electricity based on the system designs that were developed in the context of WP2 and in WP5. Cost data of the installations were provided by CONVERT.

1.2. Boundary Conditions

Generally, Agri-PV is approached in three ways regarding its energy use:

A. mainly for the self-supply of a farm,
B. for extended self-supply, increasing the self-sufficiency while excess energy is sold or otherwise distributed,
C. as an investment project, utilizing the farm surface for a larger PV system, with valorisation through a feed-in tariff, energy communities, or power purchase agreements.

The landscape of Agri-PV solutions has evolved considerably since the project was conceived in early 2022. Many systems of various sizes have been installed since, with the scale of projects growing considerably. The focus of early systems was on category A and B [1], and this was also the main expected use when the current project was proposed. Meanwhile, investors enter into the business, and category C forms the focus of installations, provided that financial conditions are made available that enable predictable earnings. Notably, in the recent tender in Italy, which was based on funds of the EU Resilience program, systems of a larger size were offered; details can be found in section 3.3.4 and the cost analysis based on the published take prices in section 4.6 below.

At the same time, the electrical systems and hence, electricity markets were and are undergoing rapid changes. As more renewable energy sources are being installed, with the pace of installation varying greatly between countries, price fluctuations tend to increase, frequently even leading to zero or negative prices in the merit-order system at times of high renewable generation, an effect sometimes referred to as “cannibalisation”. This lowers the capture rate, i.e. the financial benefit of direct grid injection at the time of generation. At other times, natural gas-powered generators are setting the price in merit-order markets, with an upward price trend owing to fuel pricing.

Arguably, short-term (intra-day) fluctuations will increasingly be compensated by an increase in the installation of batteries that enable peak-shifting between day and night times. This is expedited by the fact that battery prices have reduced considerably in recent years, making the installation for prosumers much more affordable. In combination with the price fluctuations, this sometimes even leads to good business cases for the installation of grid-stabilising batteries, with the boundary conditions strongly dependent on conditions and regulations of local markets. The latter is being addressed by commercial investors, and large PV systems, including Agri-PV, are often financed by them as well. This also leads to an increase in system sizes, with “typical” Agri-PV systems now becoming much bigger than those that farmers would install primarily for self-consumption. This report does not consider options for extended use of batteries for flexibility trading, grid stabilisation or storage beyond delayed injection intra-day, as the contractual and financial implications of these would be complex and speculative. Additional revenues may be possible through these mechanisms.

The present report goes into more detail on this in the country- and system-specific sections of chapters 3 and 4, respectively. In short, one has to acknowledge that grid injection at the time of generation is not a reliable source of revenues anymore; it is basically limited to cases where a sufficient feed-in tariff is guaranteed. Further, the variability of market conditions allows limited prediction of future revenues, casting some doubt on any business plan for the operating period of the PV systems. While funding and subsidy conditions for a given project are fixed for a number of years, they are undergoing frequent changes when it comes to new installations. Thus, the present study should be viewed as a snapshot in time rather than a prediction of the future. All market-related information underwent a review shortly before release in order to ensure that the basis for this present analysis is up to date.

1.3. Document structure

Chapter 2 outlines the methodology of the analysis, starting with a stepwise approach and then explaining the modelling of the different components. Chapter 3 describes the collections of necessary base data, including cost parameters, financial conditions and boundary conditions in the different markets regarding different energy utilisation schemes. Chapter 4 provides the approach for the analysis for the different cases that are considered, and the corresponding results. The overall results are summarised and discussed in Chapter 5, while Chapter 6 provides conclusions and an outlook.

1.4. Reference Material

The present analysis links to the KPI definitions and cost targets of Deliverable 7.3, “Definitions and KPIs for Agri-PV plants” that is available on the SYMBIOSYST website [2].

2. Methodology

2.1. Approach to Use Cases

When analysing the potential of Agri-PV to contribute to the earnings of a given farm, we take the following steps, with some variations of the order possible:

1. Generation potential: determining the useful density of installation in power per hectare, considering the type of crops and the permissible land coverage ratio, and multiplying it with the available surface area of the farm to determine an upper limit of the system size. This is then used to calculate the energy yield year-around, resulting in a time series with hourly resolution. For the demonstration cases of this work, this is kindly provided by the partners of WP2 based on modelling.
2. Consumption profile: determining the electricity consumption of the farm with a time resolution that matches the generation. If that is not available, it can be estimated based on typical time profiles of the respective farms. The relevant electricity consumers are integrated in the calculation.
3. CAPEX: calculating the costs of all hardware components based on market data and data provided by the partners, e.g. for the trackers, as a function of the system size. This consists of fixed per-power costs and variable costs that are linearly interpolated, e.g. for inverters. Similarly, for batteries a linear function of the capacity is used. The costs for the installation works are added. On the positive side, subsidies are taken into account, which may bring boundary conditions e.g. for the sizing.
4. OPEX: calculating the operating expenses as a fraction of CAPEX per year based on estimations of lifetime and maintenance and repair needs.
5. Financial boundary conditions: The percentage and costs of equity are determined as well as the interest rate for loans. In this study, we are using constant parameters to ensure comparability between the cases in terms of weighted average cost of capital (WACC). Investment subsidies are considered where these can be obtained; they may be contingent on the fulfilment of certain criteria or subject to tendering.
6. Energy market considerations: Obtaining the hourly energy market price for a reference year (for sales), and the purchase price for electricity from the grid. Where feed-in tariffs are offered, they provide a fixed sales price. Equally, supply contracts with fixed prices are considered if they provide a viable option.
7. Analysis of energy use: In addition to the use on farm, energy communities or PPAs are considered and time series of sales price are determined. A choice is made to filter for relevant cases based on a first estimate of LCOE and earnings potential, while taking into account size limitations like the extent of the energy community.
8. Optimisation study: conducting an optimisation over the sizing parameters for PV system and batteries in order to determine the financially optimal configuration. The analysis also yields information about the parameter dependence and potential trade-offs. Since this is a study in-principle, it is based on linearised inputs, not on specific choice or placement of components. If of interest, this discretisation can be performed eventually.
9. Analysis for financial viability: determining whether the results are sufficient to warrant a business case. Sensitivity and critical-parameter analyses can lead to a review of any of the parameters determined earlier.

2.2. Performance Indicators

2.2.1. Energy use

Key parameters to assess energy flows for PV prosumers are

- the self-consumption, i.e. the share of the own generated energy that is used directly on the farm or within an energy community.
- the self-sufficiency, which is the amount of the own energy consumption that can be covered by the PV system.
- the degree of peak shaving, meaning the reduction of consumption peaks that can lower the peak consumption costs which exist in most countries. In the present study, we have not observed any significant impact of peak costs.

All energetic parameters are influenced by the time profile of generation and consumption in combination with the use of a storage battery for energetic and financial optimisation. These flows are thus calculated and optimised in a model with hourly resolution in combination with component sizing, see section 2.3.

2.2.2. Net Present Value

Net Present Value measures the value of an asset by adding the initial investment as well as the present value of all the future cash flows that asset will generate, considering discounting. The present value of a cash flow depends on the interval of time between now and the cash flow because of the time value of money. In our simplified analysis, we are assuming that all investments, uptake of loan and associated costs are taking place in Year 0, whereas real projects will obviously require a certain time during which all purchases are made, fees are paid, loans are taken up, etc. End-of-life removal and disposal costs are not included at this stage.

2.2.3. Return on Investment (ROI)

In this study, an NPV-adjusted (discounted) ROI is used as a primary metric to assess investment cases. It is calculated as the sum of all discounted investments, costs and earnings (i.e., the NPV), divided by the initial investment volume. Just as the NPV, it represents a value in present (at the time of investment) terms. Since the scaling of the assets is an important part of this study and can span more than an order of magnitude in each component, revenues must be related to the investment volume in order to be meaningful from an investor's perspective.

2.2.4. Levelized Cost of Electricity (LCOE)

The levelized cost of electricity (LCOE) is the constant price per unit of energy that would yield a net present value of zero for the project [3]. It is a valid measure for the average discounted cost of a unit of electricity of the respective system and hence provides a good reference to compare generation costs. It can unfortunately be misleading since not all of the generated electricity provides the same economic benefit, especially not energy that is to be sold at times when the grid price approaches, or even falls below, zero. Sometimes, levelized avoided cost of energy (LACE) is used instead, which is a measure of value only accounting for the discounted avoided costs. As such, it is market-dependent and more difficult to assess. Other criticism concerns the dispatchability of PV electricity, or lack thereof. Details can be found in [4]. A possible correction can be made by considering the capture rate, i.e. the volume-weighted average market price (or capture price) divided by the time-weighted average price for electricity over a period. It is generally below 100% and has decreased in recent years. We are using LCOE only as an indicative figure of merit to assess whether Agri-PV

can be cost-effective in a certain setting, not as an eventual KPI, since it is not a good indicator of profitability.

2.2.5. Pay-back Period (PBP)

From a cash flow analysis of the project, the point in time can be determined when the initial investment has been earned back in full. This is considered for two separate cases: a) the equity payback, giving priority to the own funds, and the payback of project investments as a whole, including funds provided by a loan. Since here we are assuming a low equity share of 20%, the former is relatively short. Note that subsidies are not considered part of the payback calculation.

2.3. Cash Flow Spreadsheet

To assess costs and benefits in a simple manner, an Excel spreadsheet is used to calculate cash flows. It gives an indication of the main cost parameters and returns and allows to check on the influence of the main factors and to test sensitivities quickly. The calculation of annualized values is based on fixed input parameters for yield, expenses (OPEX and CAPEX), discount and inflation rates over the lifetime of the asset. However, it can only handle fixed or simple annualized parameters. What is required for a more detailed analysis and optimisation is a tool that can match supply and demand, and calculate costs and benefits, on an hourly basis, while conducting parameter variations for an optimisation, as described below.

2.4. Optimisation Model for Energy Flows and Costs

To enable effective sizing of assets in renewable energy systems, specifically for steps 8 and 9 above, a specialized modelling software has been developed by KUL in the Python language, *HyPEroptFarm*, which was also used in the Hyperfarm Horizon 2020 project[5], addressing the defossilisation of farms by different techniques also including hydrogen use. The tool integrates different open-source packages and datasets. It operates on various time-dependent inputs such as the electrical consumption profile of a given site, the PV generation profile of the location and the carbon intensity of the grid the system is connected to. Subsequently, various configurations of PV installations and battery storage systems, are subjected to a rigorous assessment of their efficacy and cost-effectiveness. This is integrated into a multi-objective optimization for both the PV installation and the storage system. Scaling variables are the size of the PV system, the battery capacity and the nominal power of the inverter. Figure 1 shows the approach conceptually.

The development of this software was motivated by multiple factors. First of all, most openly available software only focuses on maximizing the financial aspects of the technical installations. As one of the focus points of agri-PV projects is the decarbonization of the agricultural sector this software needed to incorporate multi-objective optimization. These objectives can be flexibly selected by the user from the list of available key performance indicators (KPIs) calculated by the software, as described in subchapter 2.2. *HyPEroptFarm* employs a state-of-the-art genetic-algorithm-based optimization algorithm (NSGA-III) that is capable of handling all types of decision variables and efficiently explores the Pareto-optimal front. The optimal design parameters are determined through an iterative process involving a techno-economic analysis, whereby hourly generation and consumption data, with the associated costs, are matched. This analysis employs a customizable range of suggested values for each variable, then performs the analysis and computes all KPIs.

2.4.1.Input data

In order to perform the technical analysis, *HyPEroptFarm* requires a set of input data. The three main categories are: (1) electrical load profiles, (2) PV generation profiles from the location of the site, and (3) the

carbon intensity of the electrical grid the system is connected to. The software does not handle the curation of these datasets; this is the responsibility of the user. All these datasets should have the same resolution and should not contain any missing data. In the present study, hourly resolution is used throughout.

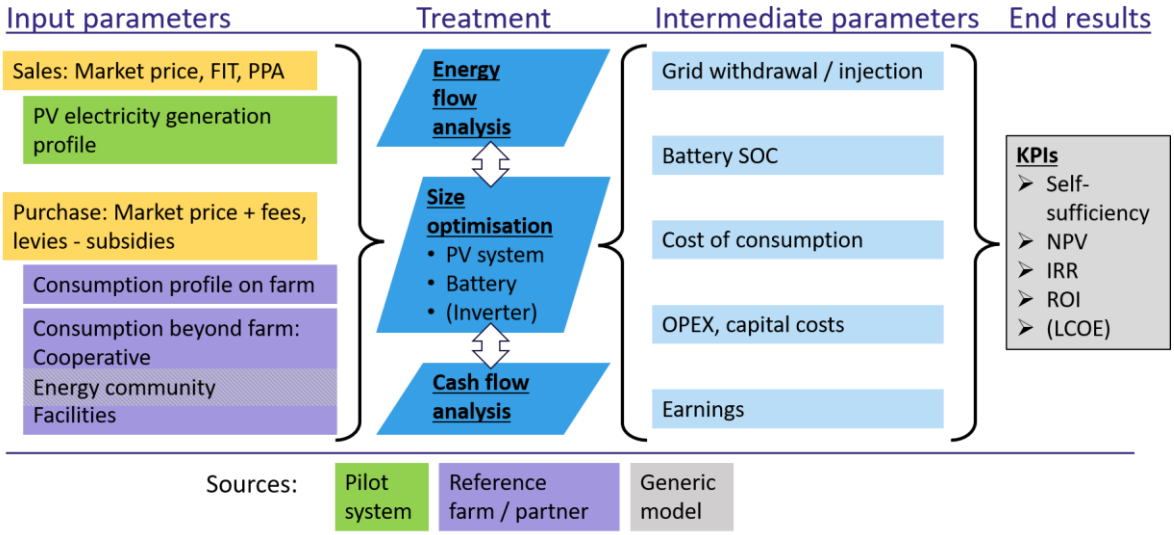


Figure 1: Parameters and treatment steps of the optimisation study

The electrical load profile of the site, i.e. the hourly electricity consumption in kWh over the course of one calendar year, is the core input to the analysis. In case the site does not already provide the PV production profile, the weather data of that specific location is acquired through the Photovoltaic Geographical Information System (PVGIS)**Invalid source specified.** and converted to a generation time series by modelling the specific settings of the system (orientation, inclination, size in kWp). In case the site already has production capacity data, an electrical generation profile can be submitted in a similar format to the electrical load data.

To be commensurate with the generation profiles, all load profiles are imported with an hourly resolution over one representative year (8760 hours), consistent with common practice in Agri-energy modelling. We are using the calendar year 2025 as the basis, although some data of other years are used to generate typical profiles where latest data were not available.

For simplicity, the optimisation model uses a fixed DC-to-AC loss of 14%, which may seem rather high for today's systems. However, on the PV side this includes a provision for degradation, where 0.5%/year lead to yield losses of 5% averaged over the lifetime, and on the battery side the effect that the battery-internal losses are not accounted for separately; this is in line with typical roundtrip efficiencies of 92%. These losses are thus lumped in the DC/AC ratio.

2.4.2.Optimisation Goals

This study uses NPV and discounted ROI as target variables, to address two different questions: How much can be earned on a farm, and what is the maximal return based on the initial investment. The former is crucial from a farmer's perspective, since he has a finite area at hand from which he can generate revenues, albeit with a fixed limit. The latter is more relevant for an investor, since he can choose from different places of deployment and different sizes, and will want to opt for the best financial outcome in relative terms. All

revenues used in this study are pre-tax, since the main aim of the optimisation study is sizing, and taxation can vary greatly by case. Equally, insurance costs are not included.

2.5. Use Case Selection

The present work develops use cases based on the farm types that are represented in the pilot installations of SYMBIOSYST. Table 1 shows an overview of the cases that are analysed. All open-agri systems use solar trackers above the crops, whereby only Scalea uses fully opaque modules. Battery storage is an option that is considered for each case in a sizing study. Details about the choices, geographical boundaries and parameterisation can be found in chapter 4. In each case, the goal is to outline how the approach can be generalised beyond the specific demonstrator. The cases considered in this study are:

- Open apple orchard with high trackers, Bolzano area (Northern Italy)
- Open citrus fruit orchard with high trackers, Scalea area (Southern Italy)
- Open lettuce/broccoli farm with low trackers (Spain / Catalonia)
- Closed greenhouse for tomatoes with fixed PV panels (Belgium / Wallonia)

Table 1: Overview of use cases related to each pilot installation

Location	**Type**	**Self-consumption**	**Energy community**	**Power Purchase Agreement**	**Grid injection market | FIT**	
Bolzano	open apples orchard	X	with SBB data			X
Scalea	open, citrus fruit	X		X		X
Barcelona	open, lettuce	X	generic		X	n/a
Mons	closed, tomatoes	X (restaurant)	n/a		X	

The pilot provides the scaling in terms of power per hectare and the electricity generation time profile. For each demonstrator, providing energy for the farm itself is the highest priority, since the avoided costs of purchase are more profitable than any other use. Conversely, grid injection at market price is the least favourable use since the remuneration is generally low and generates an insufficient payback. If a feed-in tariff is provided, it can be sufficient to finance an agri-PV system in combination with the self-consumption, often supported through investment subsidies. If this is not the case, secondary energy uses through third parties can provide a viable alternative, either through an energy community with suitable partners nearby, or through power purchase agreements (PPAs). For the former, the community is treated as one entity with an enlarged scope and joint consumption. The latter is treated as a case of energy sales with a specific contracted tariff.

2.6. PV Generation Modelling

The modelling of the annual time profile of energy generation was performed by LUCISUN in PVsyst based on data of WP2 and WP5 of the project for the cases of Bolzano and Barcelona. For Scalea, the data were provided by 3E. The models account for the model performance as a function of irradiance and temperature based on the local climate, including rear-side (albedo) irradiance if bifacial modules are used, and they use a model of the tracking, including backtracking to avoid mutual shading, to determine the optimal inclination at each time. Mismatch losses, soiling and angle-of-incidence effects are included as well. At this stage of the project, this is done with an optimal setting for PV yield. As tests are progressing, it may be necessary to modify the

tracking algorithm to include backtracking (or “anti-tracking”) allowing more light to pass through to the plants at certain times of the day or year, thus reducing the electrical yield.

2.7. Consumption Profiles of the Project

For the analysis of the Bolzano area, consumption profiles of various farm types were provided by our partner SBB. This includes dairy, apple farms and wineries. In this report, we focus on apples farms and wineries for generation since they would use the PV systems with trackers developed in the project. All farms have relatively small energy consumption and can be supplied with a fraction of the energy the pilot installations can generate. Hence, the three cases below have been identified as realistic combinations with nearby energy consumers to showcase the effective use of the electricity generated on the farms.

2.7.1. SBB Headquarters

SBB has provided the consumption profile of their own **headquarters** which is a practical case of a sizeable nearby consumer. It consists of a 6-storey building with a floor area of 720 m² in which approximately 135 employees are working. A PV system of 11 kWp is installed on the roof, covering only a small part of the electricity needs of 215 MWh in a reference year. As is typical for this type of building, main electricity loads are the HVAC system, offices, lighting and additional appliances. The main load occurs during daytime on working days, with lower consumption on weekends, as Figure 2 shows. The fact that air conditioning is present causes consumption to be high on sunny days mainly in summer, with a typical shift to later hours compared to the solar generation.

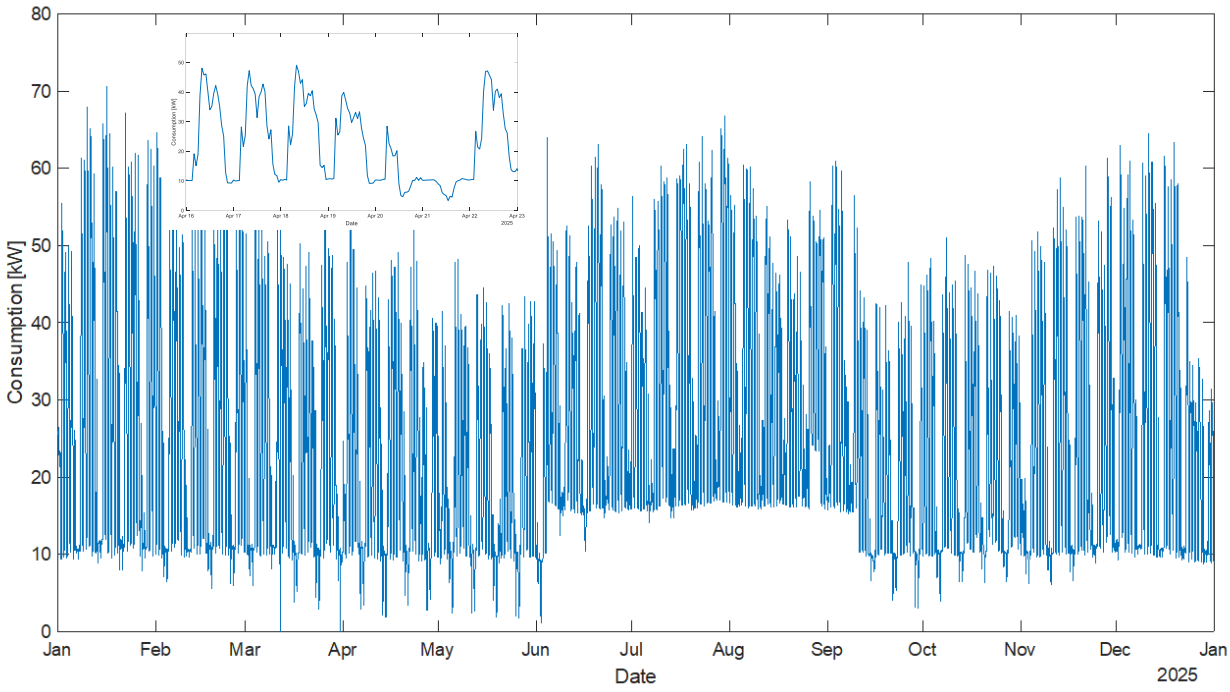


Figure 2: Hourly consumption data of the SBB headquarters for the year 2025. The insert shows the third week of April.

2.7.2. Fruit Cooperative

SBB also provided the technical information and consumption profiles of the **Frubona fruit cooperative** which operates several sites in the area nearby the Bolzano pilot for apple storage, handling, sorting and packaging. Their electricity demand is therefore closely linked to the apple harvest, the cold chain and warehouse utilisation. Unlike many conventional industrial consumers, the electrical load is not only determined by production hours, but also by year-round or multi-month storage processes. The annual intake is around 50 000 to 60 000 t of dessert apples; for 2025, 60 084 t were reported. The total storage capacity of the sites considered amounts to around 44 120 t. Main electricity consumers are: refrigeration, cold rooms, fans, controlled atmosphere systems, compressed air, pumps, packaging and sorting lines, electric forklifts and handling equipment. The cooperative is already operating on-site photovoltaic systems with around 4.16 MWp of installed capacity across the sites considered. They also own battery storage systems with a combined capacity of around 3.38 MWh and 812 kW of power. As Figure 3 shows, the energy consumption (net grid withdrawal) varies greatly over the course of a year, being highest at the time of maximal fruit processing and storage, and lowest when the storage facilities are near empty. Daily, it is lowest on middays of (apparently) sunny days, reaching zero at times of overall low consumption. Despite the sizeable on-site systems, more energy can be provided to them by agri-PV since the annual net grid consumption still amounts to about 5 GWh, as will be outlined in the analysis section below.

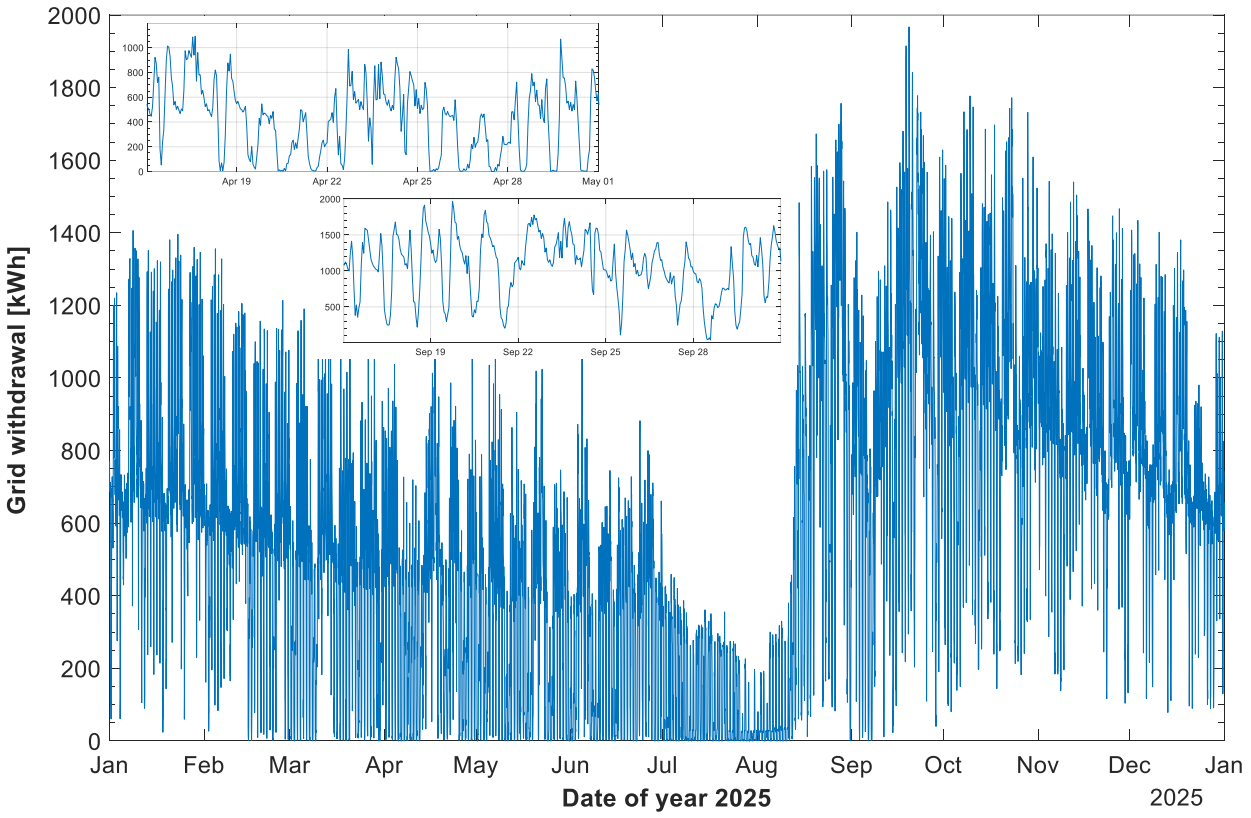


Figure 3: Hourly net grid withdrawal of the Frubona cooperative during the year 2025. Insets show the second halves of April and September, respectively.

2.7.3. Bolzano Energy Community

A hypothetical **energy community** load profile was developed using measured electricity consumption data from the Bolzano area provided by SBB. The community is composed of three demand categories: private households, apple/wine or direct-marketer farms, and dairy farms. The proposed community structure includes private household profiles scaled to represent a larger number of households, together with several agricultural profiles. Based on the available data, the final generated community profile consists of the data of 213 entities, as outlined in Table 2.

Table 2: Constituents and total consumption of the Bolzano energy community

Category	Number of profiles used	Scaling approach	Annual consumption [kWh/a]
Private households	2	scaled to 200	475 431
Apple/wine/direct-marketer farms	5	used at original measured scale	17 672
Dairy farms	8	used at original measured scale	146 415
Total energy community	**15**	**combined profile (213 entities)**	**655 196**

For the consumer farms, the measured or processed load profiles were used directly at the original farm scale represented by the data. For private households, the available measured profile was scaled by a factor of 200. The final profile contains 8760 hourly values for the year 2025. Where the original data covered more than one year, the most complete available source year was selected, converted or resampled to hourly resolution, mapped to 2025, and used as a representative annual load pattern. The resulting profile is therefore a representative annual profile based on the most complete available source year, not a climatological or multi-year average profile. The monthly totals can be seen in Figure 4, whereby the annual variation is fairly limited.

Figure 5 shows the hourly data of a week in spring, whereby the date mark indicates midnight. Typical morning and evening consumption peaks can be observed for the households and dairy farms (milking and cooling).

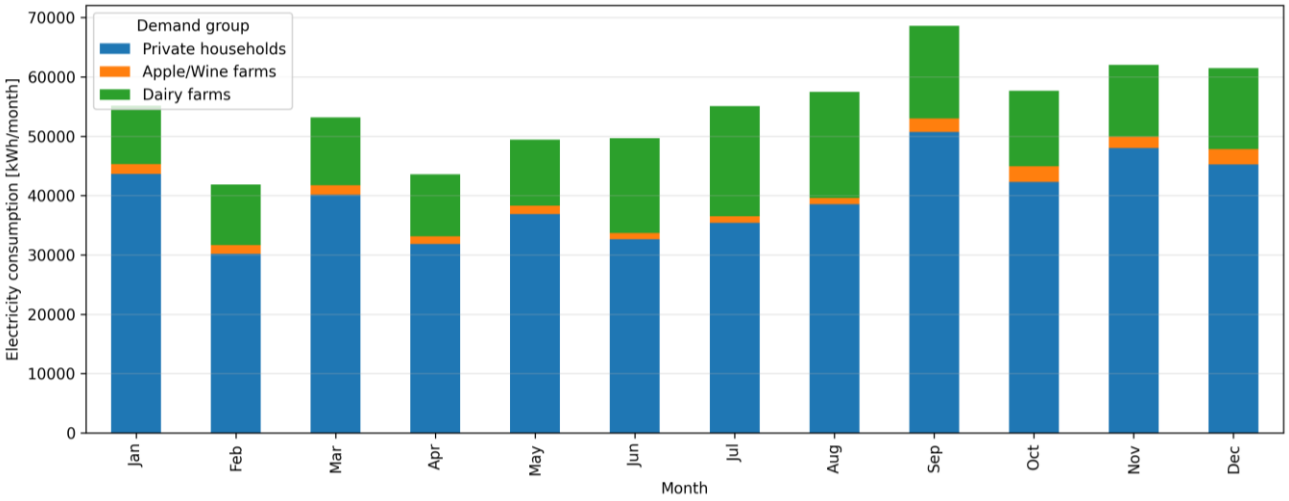


Figure 4: Monthly totals of electricity consumption for the three groups of consumers.

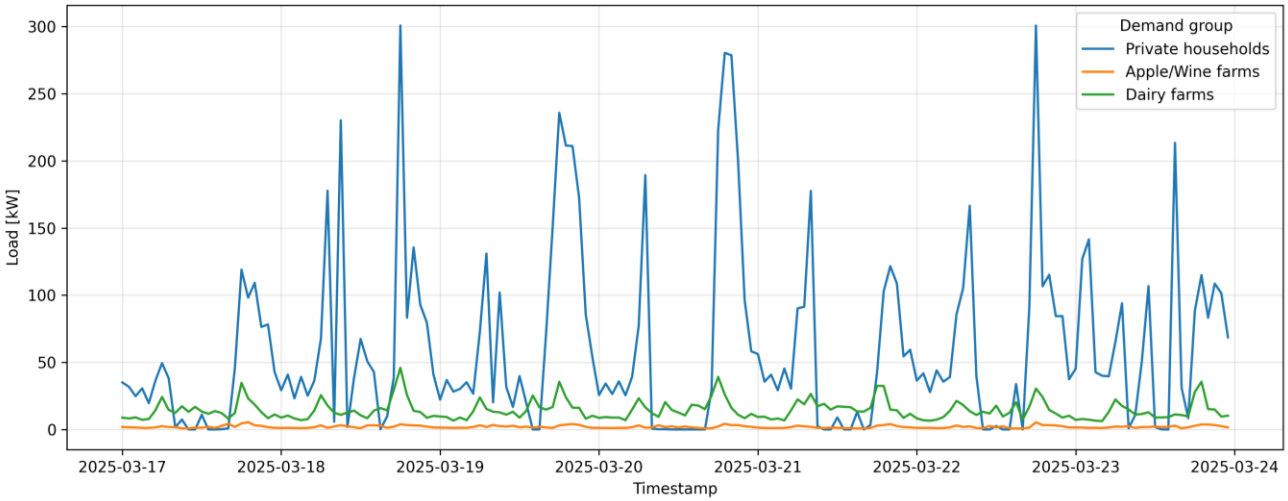


Figure 5: Hourly consumption profiles for a representative week in March, per group.

2.7.4.Consumption modelling (citrus farm)

The Scalea use case represents an open Agri-PV system for a citrus orchard in Southern Italy, designed around a traditional 3D tree configuration and a strong self-consumption logic. According to the proposal, part of the generated PV electricity is intended to be used directly on site for electrically powered cultivation equipment, including tractors, pumps, compressors, and related auxiliary systems.

Since no measured time-resolved electricity consumption profile was available for this use case, the electrical load profile is developed using a bottom-up modelling approach, based on the identification of farm-level energy services and their translation into time-resolved electricity demand. The objective of this approach is to construct a realistic representation of farm electricity consumption, independent of photovoltaic (PV) generation, while allowing for later analysis of PV-load interaction.

The load generation methodology is based on the following principles:

- the main electricity uses explicitly mentioned in the proposal were retained;
- annual energy demand was estimated separately for each end-use;
- the annual demand was then distributed into an hourly profile according to:
    - seasonal agricultural activity,
    - likely operating hours,
    - and the intended direct use of PV electricity on site.

This results in a synthetic but physically interpretable load profile that can later be refined when more detailed partner data becomes available. The modelling considers a 1 ha irrigated citrus orchard located in Southern Italy. The system boundary includes all on-site electrical loads directly related to agricultural operations, namely:

- Irrigation pumping, as the dominant seasonal load;
- Fertigation / small pumping, representing minor water-related auxiliary demand;
- Compressor use, associated with pneumatic tools or spraying-related applications;
- Electric tractor or machinery charging, representing the electrification of mobile farm equipment;
- Auxiliary loads, including control systems, valves, and small continuous electrical services.

Large post-harvest processes (e.g. centralized cold storage) are excluded, as they are not explicitly included in the Scalea demo description.

Load inventory and parameterization

Each electrical end-use is characterized by a set of parameters including rated power, operating schedule, seasonality, and control logic. Where detailed site-specific data was not available, values were selected based on literature and typical agricultural practices, ensuring transparency and reproducibility. Irrigation is the dominant load and is modelled based on annual water demand and hydraulic energy requirements. Details of the calculation can be found in the Annex.

Based on this assumption and the simulated irrigation schedule, the application of the methodology to the Scalea case study results in a total annual irrigation demand of approximately 975 mm (9,750 m^3/ha), distributed over 39 irrigation events. This corresponds to an annual electricity consumption of approximately 1,755 kWh/ha. These values represent the gross irrigation requirement under simplified assumptions, including uniform climatic input and the absence of rainfall contribution. The resulting hourly pumping profile is used in the subsequent analysis to evaluate the interaction between irrigation demand and on-site energy generation. The assumptions adopted for the initial hourly profile generation for a 1 ha reference case are summarized in Table 3.

Table 3: Assumptions for time profiles of main consumers in the citrus orchard

Load component	Assumption basis	Power level	Operating logic	Indicative annual energy
Irrigation pump	Seasonal irrigation demand distributed over irrigated months	7.5 kW	Active mainly from April to October, shifted to PV-rich daytime hours	User-defined / calculated
Fertigation / small pump	Minor support pumping demand	1.0 kW	Short daytime operation during irrigation season	User-defined
Compressor	Intermittent agricultural equipment use	3.0 kW	Used on selected working days during active season	User-defined
Electric tractor / machinery charging	Charging of electrified farm equipment	7.0 kW charger	Charged on operation days, preferably around midday	User-defined
Auxiliary loads	Controls, monitoring, valves, small equipment	0.1 kW	Constant base load throughout the year	Calculated from continuous operation

2.7.5. Electric tractors

The electrification of tractors can contribute to the decarbonisation of farms whereby the on-farm electricity consumption increases by a moderate degree. Meanwhile, several companies offer such vehicles in different sizes. However, the typical usage pattern of tractors on farms makes this task quite challenging. It consists of low- to moderate-intensity use like transport duties, often with varying types of trailers, on-field use like seeding, fertilization or pesticide spraying. In addition, there are high-power uses like tilling which are often taking place at few times in a year, then with long work hours, at least on large farms. Farmers generally expect a very high availability with few permissible interruptions.

Although electric tractors are efficient in their use of energy, electricity consumption per km can amount to 1...1.2 kWh/km in road use and 4...7 kWh/km in tillage for a medium-size tractor. E.g. a vehicle with 5 t of dry weight and 112 kW max. power is used in [6]. The consumption in tillage amounts to 16...28 kWh/ha of treated surface. As a practical example, the Fendt e100 V Vario provides 55 kW of power and holds a 100 kWh battery, which can provide 4...7 h of operational autonomy, while enabling recharging with up to 22 kW from AC, or in principle even 80 kW with a DC charger (20...80% of capacity) [7]. This and the limited width make the tractor very useful for orchards and small farms, although CAPEX for such a vehicle is a concern and currently prevents widespread use.

For the small farms with orchards or lettuce considered in this study, the battery capacity is sufficient, since a farm of 2 ha would require less than 70 kWh on days of heavy use, of which there are few in a year, and even less in everyday use, dependent on driving distances and the type of tasks that are performed. A simple estimate shows that the overall annual energy consumption would be between 1 000 and 3 000 kWh, adding significantly to the electricity use, but not changing the overall picture regarding the farm's energy needs very much.

In larger farms which require larger tractors and/or extensive periods of use, such vehicles can consume up to 5 000 l of diesel fuel in a year. However, this does not apply to the use cases based on the demonstrations of SYMBIOSYST owing to the limited size of the farms under consideration. With an electrified tractor, this would translate into an order of magnitude of approximately 20 MWh per year. The problem here is that the required autonomy, i.e. time-availability in heavy use, cannot yet be reached given available battery capacities and charging powers. Advanced solutions like battery swapping in the field would be required, which are not offered commercially at present. Maintaining fast chargers or replacement batteries would be costly and is unlikely to be adopted by farmers, given that they would only be fully utilized on few days of a year. Rental concepts would be conceivable if corresponding standards can be established.

2.7.6. Robots and precision tools

Agricultural robots are also an option to reduce fuel consumption on a farm, combined with electrification. They can take over many of the tasks that are traditionally performed with tractors, providing autonomy while operating in the field and potentially reduced energy consumption. They can be grouped into tractor-like solutions and other skids as platforms on which different appliances can be installed. Examples of the former are "Farming GT" by *farming revolution* (DE) [8] and "Robotti" by *AgroIntelli* (DK) [9]. Both feature variable working widths, whereby the Diesel-electric hybrid Farming GT specializes on weeding, while the Robotti is designed to connect various appliances that are also used on conventional tractors. For the latter, a techno-economic analysis has been published, albeit based on Diesel engines [10]. Conceivably, both vehicles can be electrically driven, using battery swapping for high-power or long-duration uses. The energy consumption would be comparable to tractors in light use, see above.

As an example for a smaller all-electric skid, "Amiga" by Bonsai Robotics is considered here [11]. The larger version "Amiga Max" features a 29 kW 4x4 drive with a swappable 7 kWh battery that can provide autonomy for up to 8 h. Bonsai also offers larger equipment specifically for use in orchards which is powered by Diesel engines for tasks like sweeping, collecting, spraying and mowing, and can conceptually be electrified. No consumption data are provided for these tools. An overview of several farming robots is provided in [12].

Given that these vehicles are used part-time and average power consumption is moderate, it seems fair to estimate that a robot would contribute a few hundred kWh/a to the energy consumption of a farm. Robots are thus not a major energy consumer and can be supplied with few square meters of PV modules. The present study assumes an annual consumption of 700 kWh/a for each small vehicle.

3. External Data Collection and Sources

3.1. Electricity market and CO_2 intensity

Day-ahead electricity market prices are available from the ENTSO-E Transparency Platform [13] under an open-source license (CC-BY 4.0) for free use. We obtained hourly data from the relevant bidding zones for the calendar year 2025. Further, the aggregated generation per type of source is used to enable analysis of the competition between carriers. Hourly carbon intensity data were obtained from ElectricityMaps.com [14] corresponding to the market data for the zones Italy-North (IT-NO), Italy-South (IT-SO) and Spain (ES), for the locations of Bolzano, Scalea, and Barcelona, respectively.

3.2. Cost parameters

3.2.1. Basic cost categories

We are breaking down costs of the system as a function of the system size in kWp, which we use as the primary scaling variable. It should be noted that the present study provides an analysis in principle, not a detailed planning for a specific system, where differences according to geography, local regulations and commercial boundary conditions will lead to deviating results. We are thus keeping some cost items constant across the cases when variations are minor, aiming to maintain comparability while focusing on main differences in the setup and location. Generally, costs per item are either fixed or interpolated linearly between the maximum and minimum size of the system. We are providing a cost breakdown for each use case in chapter 4.

Details for the main components subject to work in this project are given below. The categorisation follows the work of Schindele et al. [15], with the main categories being

- PV modules
- Mounting structures and hardware
- Inverter
- *Batteries*
- Combiner box, misc. components
- Cabling
- Site preparation and installation
- System design, management, administration costs
- Due diligence incl. yield certificate
- Legal advice
- Grid connection
- Soil protection
- Cost of tendering procedure.

Batteries have been added in this project – they have not been considered by Schindele et al., since at the time of that study (2020) their use would not have been beneficial owing to their high costs. Meanwhile these are much lower (see section 3.2.7 below), and the difference in market price of electricity between times of high injection by Renewables and off-peak times has increased considerably, improving the business case for batteries and making it interesting to install them with nearly every PV system.

The study of Schindele et al. [15] provides a detailed breakdown of costs for agri-PV systems in comparison with ground-mounted PV. Generally, the CAPEX costs for elevated agri-PV systems are expected to be higher than for conventional ground-mounted systems. Main differences include:

- PV modules, dependent on the selected type (semi-transparent, bifacial)
- Mounting structures, dependent on the selected type, with a potential offset by existing or adapted structures for other purposes like hail nets or greenhouses
- Site preparation and installation
- Soil treatment and protection

Other costs (inverters, electrical components, design and management, grid connection) are not expected to be substantially different. Notably, the costs for wiring and grid connection can effectively vary since the distances to be covered may be larger owing to the more distributed installation. We base our analysis on the estimate for general costs of Deliverable 7.3 of the present project and an own assessment of the most important subcomponents, see the following subchapters. Table 4 shows a comparison with the main reference study. It should be noted that D7.3 is based on the actual size of the demonstrators, while this present study includes the estimation of scaling effects, especially cost reductions at larger scale.

Table 4: Comparison of cost assumptions with Schindele et al. [15]

Cost comparison internal / literature	**Min**	**Max**	**Reference** [15]	**Comment**
Size [kW]	1000	1000	1038	Size dependence can be found in the case details of chapter 4
Price of PV modules [€/kWp]	191	199	290	Costs depend on transparency; max. size uses container delivery
Inverter [€/kWp]	28	28	60	Assuming 3 large multi-string inverters (large systems only)
Mounting structures and hardware [€/kWp]	198	256	405	SYMBIOSYST data; depends on height and module transparency
Electrical system	155	170	130	Cabling and connection costs dominate
Site preparation and installation	300	400	330	
Administrative and Legal	110	110	79	
OPEX as percentage of CAPEX	1,8%	1,8%	1,3%	
Total [€/kWp]	**983**	**1 164**	**1 294**	

3.2.2.Operating expenditure

For OPEX, Schindele et al. do not expect major differences between Agri-PV and ground-mounted PV [15]. Land costs (lease) are treated differently since the main purpose in Agri-PV is still agriculture, and treatment costs like mowing may be unnecessary, or are entangled with the costs for agriculture, i.e. not specifically attributed to PV. According to their assessment, OPEX costs per year amount to between 1% and 2% of the CAPEX costs. In alignment with Valmont as the partner providing structures for the utility scale and agri-PV markets, we are assuming 1.8% of the capex per year for OPEX. A sensitivity analysis for OPEX of utility-scale plants can be found in [16], where OPEX/CAPEX ratios around 2% are considered. Details of the operational aspects can be found in [17].

3.2.3. Costs of capital

For simplicity, and to ensure comparability across the cases, the financial analysis of this study is based on 20% equity and 80% loan volume, and it is assumed that all investments occur in year zero of the project. For the cost of debt, an interest rate of 4% is assumed for all cases. We put the expected equity IRR at 8%. These fixations yield a weighted annual cost of capital (WACC) of 4.8%. The inflation rate is fixed to 2% in agreement with the long-term EU goal [16]. These assumptions may be seen as somewhat optimistic. In case investment subsidies are included, the analysis further on uses the net value for CAPEX as a basis for the financial results. For several cases, they are compared directly with and without subsidies.

3.2.4. Mounting structures

For the costs of the solar trackers and their installation, data provided by our project partner CONVERT are used. They are differentiated according to system size (in kWp), height of the system, and transparency, which influences the specific costs. Table 5 shows an overview. While lettuce and broccoli only require moderately high structures, higher systems are necessary for apple and citrus fruit orchards. In addition to the increased amount of steel needed for higher structures, stronger foundations are required as well, leading to considerably higher costs for the structures with 3.5 m clearance, compared with those of 2.1 m. In addition, the tracker costs per watt-peak vary with transparency since the required number of trackers per kWp varies.

Table 5: Cost parameters for solar trackers used in the demonstrator systems

Use case	System	Panel costs €/kWp	Tracker hardware costs €/kWp	Tracker installation costs €/kWp
Barcelona	raised 2.1 m, 10% transparency	206(20 kWp) 191 (>= 1 MWp)	198	70
Scalea	raised > 3.5 m, 0% transparency	225(20 kWp) 205 (>= 1 MWp)	230	90
Bolzano	raised > 3.5 m, **10%** transparency	206 (20 kWp) 191 (>= 1 MWp)	256	90
Bolzano	raised > 3.5 m, **40%** transparency	300 (20 kWp) 279 (>= 1 MWp)	383	90
Closed APV	Venlo-type greenhouse	225 (20 kWp) 205 (>= 1 MWp)	n/a	n/a

3.2.5. Geographical considerations and electrical system

The design of the cabling needs to be based on a geographical arrangement of the PV system in terms of the ratio of width and length and the distance to the grid connection point. More distributed fields would lead to longer wires and higher associated costs and losses, while a very compact arrangement is not necessarily realistic. We are thus assuming a system of one hectare to have a length of 200 m and a width of 50 m, with the electrical connection at one short side and the inverter being at an average distance of 150 m from the string connecting point. Strings are assumed to consist of 28 PV modules, each with 54 solar cells in series, resulting in a nominal open-circuit voltage of approximately 1240 V, close to the maximum for a 1500 V rated system. A system of 1 ha thus consists of 48 strings. Notably, the DC-side voltage is always higher than the AC output voltage of the inverter (400 V for the low-voltage grid, or 600→800 V if designed to be connected directly to a transformer, see below). In terms of loss minimisation, it is thus useful to place the inverter close

to the connection point or transformer and have the long cable runs on the DC side. If run with individual cables per string, which is desirable not least for the purpose of individual monitoring, the length of wire amounts to approximately 16 km/ha. As a result, cabling costs of 40 €/kWp are used throughout, irrespective of system size and details of the use case. On the AC side, transformers can be included in the system design, generally with one unit per connection point, and are contributing a small share to the system costs. Costs for potential grid reinforcement are not included here as they are highly variable and require a sharing agreement between farmer and utility.

3.2.6.Inverters

We conducted a survey of wholesale prices for multistring inverters in February 2026 and are using a linear interpolation for the scaling of the price after adding a 25% margin. Data sources herefore cannot be disclosed for confidentiality reasons. As Figure 6 shows, the price trends for PV-only and hybrid inverters show a near-identical trend, i.e. the price of the additional bidirectional converter in hybrid systems is negligible. While inverters with powers up to 200 kW are designed to connect to the low-voltage grid with 400 V AC, those with higher powers are made for connection to the medium-voltage grid through a transformer and feature higher output voltages in order to reduce conduction losses. This study is based on the use of hybrid inverters throughout. For larger systems that require higher powers than 300 kW, multiple inverters are used. This is by price calculation only; we are not planning actual systems in this study.

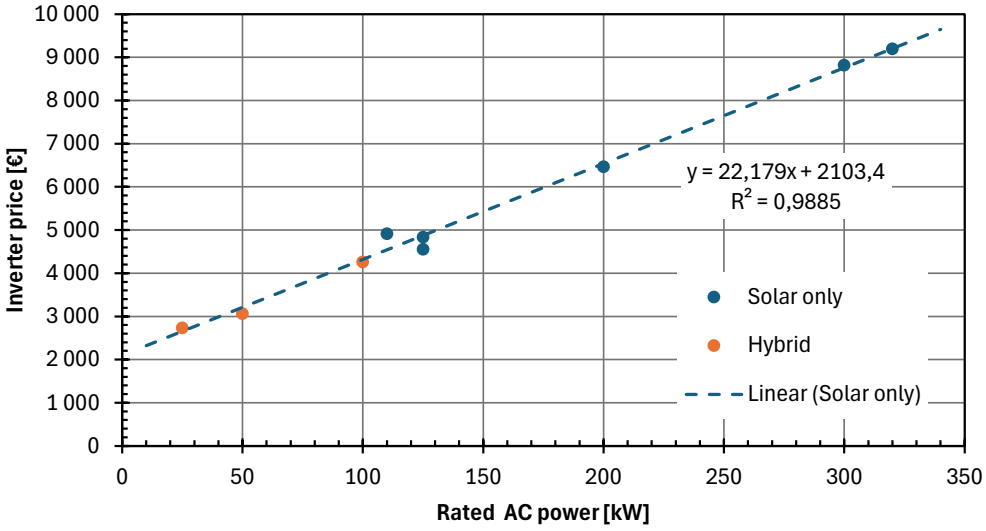


Figure 6: Inverter price as a function of nominal power for PV-only and hybrid devices. Basis are wholesale prices with a 25% markup.

3.2.7. Storage systems

Similar to inverters, the price for Li-ion battery storage systems was determined from wholesalers and is used with a 25% added margin. These systems consist of the battery and the required inverter to connect to AC, whereby the ratio of capacity to power varies between 1.7 h and 4.1 h. Since the battery represents the main cost item, no differentiation was made with respect to power ratings. Roundtrip efficiencies are approximated to be 90%. As with inverters, there is only a minor variation in price when hybrid inverters with additional MPPT converters are used, as Figure 7 shows. It is thus disregarded in the scaling study, and a linear interpolation is used throughout.

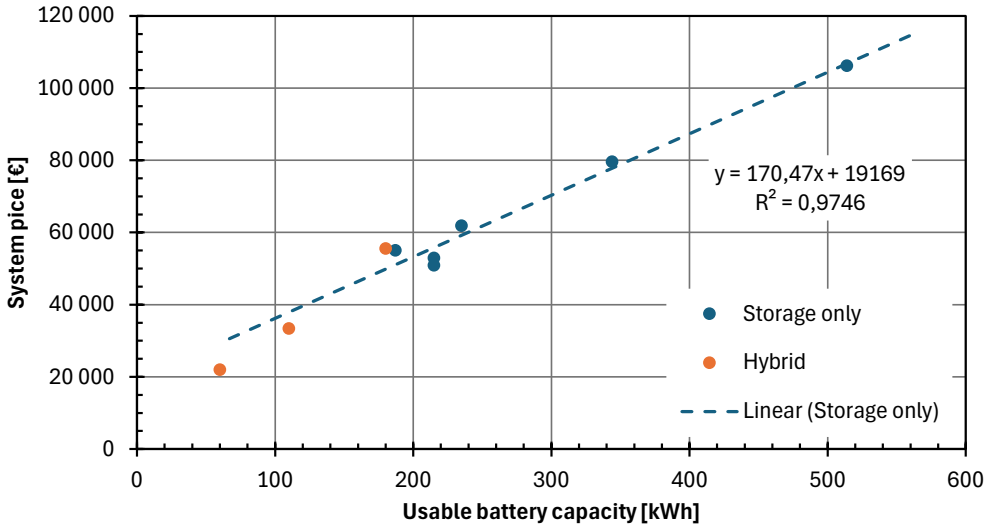


Figure 7: Price of storage systems as a function of the usable capacity.

To put storage costs into perspective, these prices amount to a minimal cost per amount of energy stored of €0.04/kWh for the largest systems (500 kWh) and €0.11/kWh for small systems (50 kWh), if the lifetime of the battery is fully exhausted, i.e. with 5 000 equivalent full cycles, corresponding approximately to daily cycling with partial capacity over the system lifetime. This is typically below the difference in price between grid withdrawal and injection, i.e. the battery operates profitably for self-consumed energy as long as it enhances the self-sufficiency significantly. However, it is above the average spread in grid wholesale prices. That is to say, it is generally not profitable to install a (larger) battery to postpone grid injection because of market price fluctuations in case of sales to the general market. This may be different dependent on the actual pricing, and secondary requirements like consumption peak shaving, continuity of operation or supply of backup power may provide additional advantages.

3.3. Country Specifics – Italy

3.3.1. Grid withdrawal

Farmers in Italy can choose between fixed and variable, time-of-use (hourly) tariffs. We are considering both options. In addition to the hourly zonal market price per kWh (Prezzi Zonali Orari, PZO), fees and levies as well as a capacity price of typically 50 €/kW is charged. The fixed price per kWh is rather high, 0.24 €/kWh. This study is basing further analysis on the ToU tariff as the cheaper option, assuming a typical farm energy consumption profile.

3.3.2. Grid Injection

In Italy, grid injection based on net metering (Scambio sul Posto, SSP) is being phased out and no longer possible for PV systems installed after 2025 [18]. Main mechanism for new PV systems is “Ritiro Dedicato” (RID) whereby energy injected into the grid is sold directly to the grid operator GSE. The remuneration is based on the hourly zonal market price (Prezzi Zonali Orari, PZO), different for Italy’s six energy zones. In this study, we are focusing on the zone of North Italy for the Bolzano site and South Italy for Scalea, owing to the localization of the demonstrators. For administration, a moderate annual fee has to be paid.

In addition to the sale at grid price, prosumers can opt for a scheme with a guaranteed national minimum price (Prezzo Minimo Garantito, PMG). For this scheme, PV systems up to 100 kW are qualified if they receive incentives, and non-incentivized systems with a power up to 1 MW. The value of PMG is set annually by ARERA and was 46.8 €/MWh in 2025. The pay-out is based on an annual balance: if the annual average price according to PZO is lower than the guaranteed minimum price, the latter is paid through an annual adjustment.

3.3.3. Energy Communities

Energy communities can represent a solution to share the generated electricity, whereby the question of ownership needs to be settled. In principle, there are two types of collectives. In a Renewable Energy Community (Comunità Energetiche Rinnovabili, CER), groups of users (families, businesses, public bodies) are sharing energy produced locally from renewables, and the surplus not locally consumed is injected into the grid under the RID, see "grid injection" above. The producer receives specific GSE incentives for energy that is shared and consumed locally [19]. The incentives for shared energy aim to maximize local self-consumption, reducing dependence on grid pricing, and encouraging energy independence. The CER must be located within the grid of the same primary distribution substation (cabina primaria) and is thus constrained both in geographical extension as in power.

The Tariffa Premio per l'Energia Condivisa (TCEC) provides a 20-year incentive for every kWh of energy generated and shared within the CER. Thereby, "energia condivisa" represents the hourly minimum between energy produced by CER generation units and energy consumed at the same time by the CER members. The tariff depends on the plant size, as Table 6 shows.

Table 6: Remuneration of energy shared in energy communities in Italy. 'Pz' is the hourly zonal market price.

Power range	**Premium formula**	**Maximum**
≤200 kW	80 + max(0; 180 – Pz) €/MWh	up to 120 €/MWh
200–600 kW	70 + max(0; 180 – Pz) €/MWh	up to 110 €/MWh
600–1000 kW	60 + max(0; 180 – Pz) €/MWh	up to 100 €/MWh

To compensate for varying solar irradiation, an additional €4/MWh is available for plants in Central Italy and €10/MWh for those in Northern Italy.

As for agri-PV in general, the PNRR (Piano Nazionale di Ripresa e Resilienza) provides a capital grant of up to 40% of eligible investment costs to support the creation of CERs and collective self□consumption systems, provided that they are located in municipalities with less than 5 000 inhabitants. These incentives are granted until 5 GW of incentivized capacity is reached or until 31 December 2027, whichever comes first. Batteries are also eligible for investment subsidies and receive a 30% premium. There is a choice to be made for the PNRR funding or for the TCEC.

For the energy sharing in a CER, the partners must form a non-profit entity that organizes the exchange and can take ownership of the assets. At the minimum, clear agreements have to be closed outlining the ownership and responsibilities. There is another energy sharing scheme where co-ownership is not required, Autoconsumo Collettivo. It is meant for users co-located at one site (e.g., in one building) and is thus not further considered here.

3.3.4. Investment subsidies and feed-in tariffs

The National Recovery and Resilience Plan (PNRR - *Piano Nazionale di Ripresa e Resilienza*) is Italy's €194.4 billion investment and reform package, funded by the EU's Next Generation EU program. This funding scheme is coming to an end with tenders that were handed out in 2026 [20]. Italy has dedicated national incentives for agri-PV systems, covering all Italian regions through the PNRR Investimento 1.1 “Sviluppo agro voltaico” (Decreto Agrivoltaico, DM 436/2023). The decree promotes innovative agrivoltaic systems with up to 40% capital contribution (contributo a fondo perduto) and/or a dedicated feed in tariff on net electricity injected into the grid. These incentives are available to farms, agribusinesses, cooperatives and related agricultural operators nationwide, with premium tariffs generally set at €93/MWh for plants below 300 kW and €85/MWh for projects above 300 kW (in 2024), which are cut in half if the 40% investment subsidy is used. To compensate for varying solar irradiation, an additional €4/MWh is available for plants in Central Italy and €10/MWh for those in Northern Italy. In the application to participate in the procedures, the applicant indicates the percentage reduction it intends to offer with respect to the relevant reference rate. While in the case of Registry procedures the percentage reduction offer is not mandatory, for participation in Auctions the reduction offer is mandatory. In both cases, the value of the reduction offer cannot be less than 2%.

To qualify for these incentives, Agri-PV systems must meet specific technical criteria to ensure the integration of agricultural and energy production, as finalized in early 2024 by the Ministry of Environment and Energy Security (MASE) and the GSE, categorized into spatial configuration, agricultural continuity, and technological monitoring:

1. Spatial & Height Requirements: The system must be designed to allow agricultural activities to continue directly beneath the solar panels:

a) Minimum Height (Crops): Modules must be elevated at least 2.1 meters from the ground to ensure the safe passage of standard agricultural machinery.
b) Minimum Height (Livestock): For grazing activities, the minimum elevation is reduced to 1.3 meters.
c) Module Spacing: Structures must be spaced to provide sufficient light and space for continuous cultivation, preventing the "industrial" footprint of standard ground-mounted solar.

2. Land Use & Productivity Limits: The plant must prioritize agricultural output over energy density:

d) Agricultural Area: At least 70% of the total project surface must be dedicated to active agricultural cultivation or livestock.
e) Energy Efficiency: The electricity production per hectare must be no less than 60% of what a standard (ground-mounted) PV system of the same size would produce, ensuring the panels are still efficient despite their elevation.
f) Total Coverage: The total area covered by modules generally cannot exceed 40% of the project surface.

The listed incentives are granted until a cumulated capacity of 5 GW is reached, or until 31 December 2027, whichever comes first.

3. Advanced Monitoring Systems:

g) Participation in the incentive scheme requires an integrated monitoring network developed according to CREA (Council for Agricultural Research) guidelines. This network must measure:

- Agricultural Yield: Annual tracking of crop productivity compared to traditional fields.
- Microclimate & Soil: Real-time data on soil moisture, fertility, and temperature.

- Water Savings: Assessment of the system's impact on irrigation needs and water conservation.

4. Subjective & Legal Criteria:

h) Eligible Entities: Primarily agricultural producers (as defined by Art. 2135 of the Civil Code), cooperatives, or temporary associations between investors and farmers.
i) New Components: The plant must be newly built using entirely new components; used or refurbished equipment is not permitted.
j) DNSH Principle: Projects must comply with the "Do No Significant Harm" environmental principle required for PNRR-funded initiatives.

Official cost assumptions for agri-PV in Italy are as follows: with non-permanent crops, +400 €/kWp vs. single tracking ground mount, with permanent crops, +140 €/kWp [1]. There are future options to obtain funding subsidies for agri-PV beyond 2026 as well, e.g. regional calls [21].

3.4. Country Specifics – Spain

3.4.1. Grid withdrawal

Farmers in Spain can choose between fixed and variable, time-of-use (hourly) tariffs. We are considering both options. In addition to the base price per kWh, an energy tax of 5% and VAT of 21% as well as a capacity price of typically 30…50 €/kW is charged. This study is basing further analysis on the ToU tariff as the cheaper option, assuming a typical farm energy consumption profile.

3.4.2. Grid Injection

Spain no longer offers feed-in tariffs or premiums for new PV plants, including Agri-PV. Electricity injected into the grid is generally remunerated through merchant (wholesale market) revenues.

3.4.3. Energy Communities – Legislation

Renewable Energy Communities are a viable option in Spain, the main obstacle being the geographical distance between the members. Partners or members are natural persons, SMEs or local authorities, including municipalities, whose primary purpose is to provide environmental, economic or social benefits to their partners or members or to the local areas where they operate, rather than financial profit. PV assets can be owned either by the community, a member (farmer), or an investor / ESCO. Key regulations are found in Royal Decree 244/2019 [22]. Installations with a combined power under 100 kWp can use a simplified self-consumption scheme with a compensation based on wholesale electricity price (hourly PVPC); larger producers need to register as generators and sell on the wholesale market. The biggest source of revenues needs to be the avoided grid withdrawal costs. In the case of collective self-consumption, all the consumers associated to the same generation unit must be under the same self-consumption modality and shall communicate to the distribution company an agreement signed by all participants, which includes the distribution criteria.

Tariff structure: The energy that is self-consumed and comes from renewable sources, cogeneration or waste is exempted from all types of charges and tolls. However, if there is transfer of energy through the distribution grid to nearby facilities for the purposes of self-consumption, fees for this usage may be established (article 9, Law 24/2013). For the pay-back of the grid-injected energy under “Compensación simplificada”, only the energy costs are considered; taxes and other fees are not reimbursed.

Geographical limitations: In collective self-consumption, the generation units can be interconnected through the grid, with the interconnection falling in one of the following options: a) the units are connected to any of the low voltage networks derived from the same transformer substation; or b) both generation and consumption are connected at low voltage and at a distance of less than 500 meters from each other; or c) both generation and consumption are located in the same cadastral reference. According to some sources, the 500 m distance is not necessarily enforced provided that condition a) holds.

When the self-consumption is carried out between near installation through the grid, collective self-consumption may belong to any of the modalities "with surplus" (article 3, RD 244/2019). Under the modalities of self-consumption "with surplus", consumers can decide to sell all electricity surplus directly on the market, or they can be compensated through a simplified mechanism (Net billing), where every month the value of the energy taken from the grid is compensated with the value of the surplus generation fed into the grid. Nevertheless, the maximum amount that can be compensated is the value of the energy taken from the grid (the energy purchased by the consumer) because the result of the compensation cannot be negative and may not offset other access fees [23].

Lastly, to help the initial development of energy communities, a specific program for granting aid to Community Transformation Offices (OTC) for the promotion and dynamization of energy communities was launched by IDAE and the program CE-Implementa (6th call) that provide grants in the form of a non-refundable subsidy to energy communities, which will be definitively received by the beneficiary once the execution of the project verified and the investment certified [24].

3.4.4. Energy Communities – Test Case

In order to assess the potential of sharing in energy communities, we have obtained publicly available household consumption data all across Spain from a dataset [25] that has been generated by in the context of the WHY Horizon 2020 project **Invalid source specified.**. To integrate them into the energy simulation, we have extracted consumption data profiles from 1 000 of these households and SMEs, and averaged them to get a typical annual consumption profile with hourly values. This was done by choosing random profiles, filtering out ones that are shorter than one year and with very low annual energy consumption below 500 kWh. Figure 8 shows the combined time series. The consumption peaks occur around 22:00 while the minima concentrate around 05:00. The energy flow simulation is then run with the energy community with a fixed number of households and a prosumer farm based on the Barcelona demonstrator as one unit, while scaling the PV power and battery capacity jointly for the entire unit. This leaves out details of the placement and associated costs, since the scaling is hypothetical and would need to be adapted to a specific setting.

3.4.5.Power Purchase Agreements

Power Purchase Agreements (PPAs) are the dominant remuneration mechanism for utility-scale PV in Spain. They are typically closed for a duration of 5 to 15 years. According to S&P Global Commodity Insights, Spain's 10-year pay-as-produced solar PPA break-even price is €38/MWh for PPAs starting in 2026. This break-even value is a critical anchor for forward pricing, as actual contracted PPA prices must generally cluster around or below this point to remain competitive. Typical PPA prices were €30…35/MWh in 2024–2025, with some offers trending below €30/MWh in recent years due to negative-price pressure. This indicates a downward trend that aligns with increasing capture-price suppression caused by high solar penetration. Spain has experienced an increasing frequency of negative-price hours, which influences remuneration. To manage this, new PPAs often include €0/MWh price floors and/or caps on the number of negative-price settlement hours. This study uses a generated typical profile to determine the earnings based on time-dependent prices as-

produced. The remuneration through PPAs with realistic injection profiles is marginally better than through wholesale prices, and not much above the LCOE of agri-PV, while utility-scale power plants have a significant cost advantage. Thus, there is no viable business case, and the scheme was not analysed further.

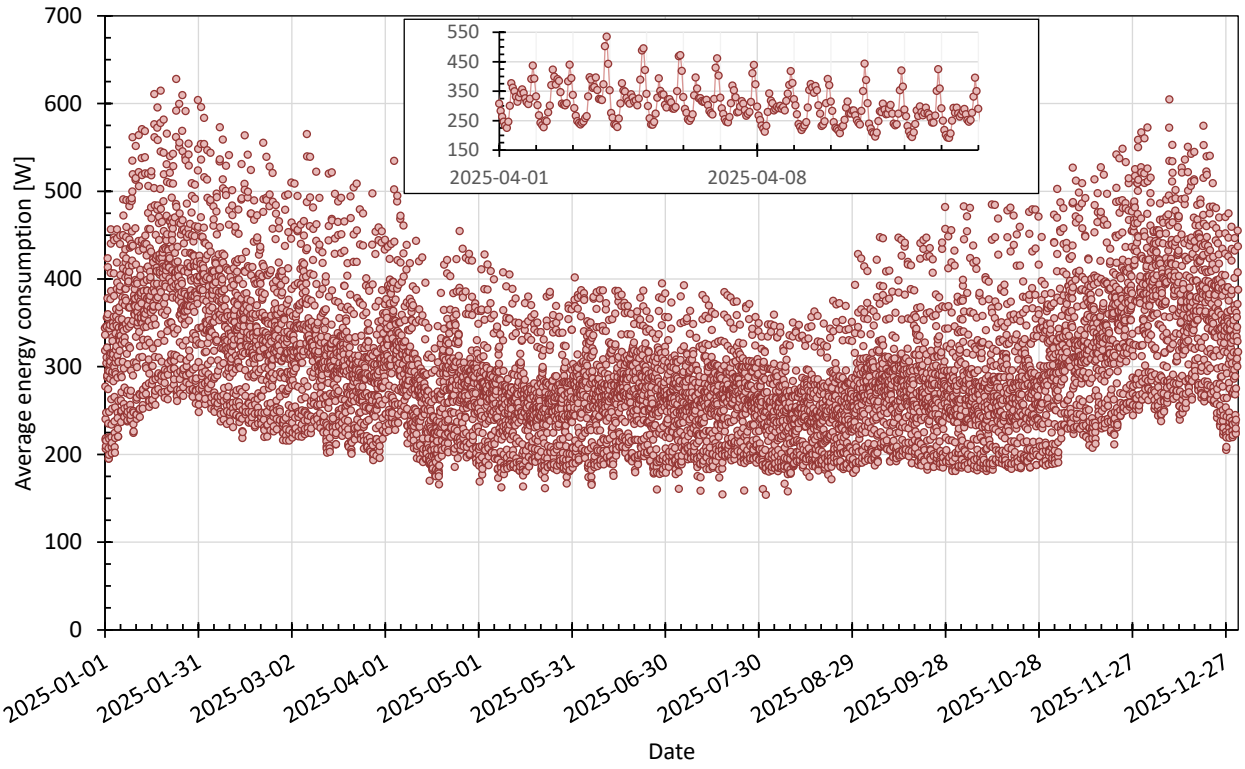


Figure 8: Annual consumption profile with hourly averages for a set of 1 000 Spanish households. The inset shows data from the first two weeks of April as an example.

3.4.6. Investment subsidies and feed-in tariffs

Projects in Spain can receive CAPEX subsidies of up to 50% if they are recognized as innovative, which includes agri-PV [26]. In order to maintain comparability between the cases, we use a 40% subsidy rate. The main subsidy program by the Institute for Energy Diversification and Saving (IDAE) only supports projects with a power of more than 5 MWp, which is too big for the family-farm type installations considered in the present study. Different regions offer subsidy programs; unfortunately, Cataluña, where the demo of SYMBIOSYST is located, is not one of them. The European Regional Development Funds (FEDER) finances regional development projects, including renewable infrastructure, with eligibility criteria including location in low population density areas, local employment impact, technological innovation, social participation (cooperatives, energy communities) and emission reduction, several of which can apply to agri-PV. Subsidies of 30…50% can be granted in annual calls in a competitive scheme.

3.4.7. Situation of agri-PV

Since late 2025, Spain amended its national Common Agricultural Policy (CAP) framework so that agrivoltaic systems are eligible for agricultural subsidies. According to the national CAP framework (Royal Decree 1048/2022 and later updates), land hosting solar panels continues to receive CAP subsidies as long as agriculture is the primary use of the land.

Schemes include direct payments, eco-regimes for environmental practices and rural development funds. This is a major development because it means that farmland under solar installations can still receive agricultural subsidies, as long as farming continues. Spain has explicitly stated (Act 31/2022) that it will promote agrivoltaics, analyse barriers (land use, CAP compatibility), and create specific lines of aid to support agrivoltaic project development. For regional support, Catalonia has adopted soft regulations encouraging agrivoltaics and ensuring crops remain productive. Specific eligibility conditions must be defined in future regulations, i.e. how much crop yield, grazing activity, or land access must be maintained. There are no explicit subsidies for the PV activities. Energy can be used on the farm itself, or sold at market price or through PPAs. Agri-PV projects are processed under the same general regulatory and permitting framework as ground-mounted PV plants, which form a major part of the country's renewable energy expansion. Large scale solar parks regularly enter the permitting pipeline, with over 5 GW of new projects submitted for environmental permitting in 2025 alone [27].

Developers must obtain several administrative authorizations, typically issued by the relevant autonomous community: (1) an environmental assessment (preliminary or full EIA depending on project size and site sensitivity), (2) construction and operation permits, and (3) land use rights such as purchase, lease, or surface rights. A grid access and connection permit is essential and often one of the most challenging steps. Projects larger than 1 MW must obtain a favourable technical report from Spain's system operator, Red Eléctrica de España, and submit detailed technical and administrative documentation to the grid operator. Spain's grid capacity constraints mean that access rights may be allocated via competitive tenders in saturated grid nodes. Award criteria may include project timelines, environmental factors, and technological characteristics, influencing which ground-mounted PV plants are allowed to connect to the network [28]. Agri-PV projects also face additional agricultural use conditions that do *not* apply to conventional ground-mounted PV [29]:

1. Agricultural activity must remain the primary land use for the site to qualify for agricultural subsidies under Spain's updated CAP framework. The land remains eligible for subsidies only if farming continues as the main activity.

2. Dual-use criteria apply, meaning solar installations must coexist with ongoing agricultural production. Technical criteria on coexistence will be defined through further regulatory development.

3. Regional rules may impose specific conditions for Agri-PV. For example, Catalonia's soft regulation framework requires:
    - Agricultural activities must be maintained throughout the life of the plant.
    - Crop yield must be kept at least 60% of preinstallation levels. Because Spain has no national agrivoltaics law, monitoring methods come from research projects and technical practice, not regulation.
    - The solar operator and landowner can be different entities.

Agri-PV can receive up to 50% in CAPEX subsidies under the IDAE program as Innovative Pilot Projects, provided that measurements and scientific reporting of results are conducted for 3 years, or for large systems of more than 5 MWp. Further to that, loans can be received for 20…40% of the CAPEX volume. Under the IDAE innovation programmes, the interest rate is 0.5% with a tenor of ~15 years. Further, the ICO (Spanish public bank) provides loans with rates between 2% and 4%, whereas typical corporate loan rates Spain are ~3.5–4% (2026) [30].

4. Results and Analysis

The energy consumption on the farm is found to be small in all cases of open Agri-PV, even if additional appliances are considered. In order to explore the economic potential of Agri-PV, we are thus employing a sizing study of the PV system and the battery as outlined in section 2.4 for all cases. The goals are to see

- if a positive return on investment can be obtained for the specific boundary conditions,
- which size category of assets is favourable, and
- what the impact of financing conditions is.

The model used here enforces equally sized steps over a large range of sizes. It can thus not be ensured that the lower-end size is truly optimal for the case. However, this has little impact on the overall finances. For the financing conditions, an investment subsidy of 40% is analysed, as it was granted in the Italian PNRR scheme.

Beyond the farms, we are doing this for energy communities as larger users of the generated energy. Here, the study is limited to the perspective of a farmer supplying the energy as a single player. There are also benefits to the community and its members which are dependent on fees and taxation; the corresponding investigation is beyond the scope of the present study. The input parameters and results for each case are summarised in a standard table format, and only the key results are discussed in the text.

4.1. Load Profiles and Consumption Patterns of the Use Cases

Before presenting the load profiles of the selected use cases, it is important to clarify the basis on which these profiles were developed. The project proposal defines the main energy uses for each use case in a qualitative manner (e.g., irrigation, machinery, climate control) but does not provide detailed time-resolved consumption data. Therefore, the load profiles presented in this work are constructed based on a combination of

- the functional description of energy uses provided in the proposal,
- data and inputs received from the demo-responsible partners, and
- additional assumptions derived from typical operational patterns in agricultural systems.

This approach ensures that the resulting profiles are both consistent with the project framework and suitable for subsequent analysis of energy matching, self-consumption, and system optimization.

4.2. Open Agri-PV - Bolzano Apple Orchard

This use case represents a high-density apple orchard system in South Tyrol, combining both traditional (3D) and Guyot (2D) cultivation approaches under a tracker-based Agri-PV installation. The system is designed to integrate multiple agricultural functions, including irrigation, crop protection (anti-frost and anti-hail), and the electrification of farm operations. The PV system consists of trackers developed in this project with a height of 4.78 m above the trees and equipped with custom-made PV modules with transparencies of 10% and 40%, respectively.

For the economic analysis, we are thus using only one density and the less transparent modules which require less trackers per area. The detailed cost assumptions can be found in Table 7, based on details provided in section 3.2. Based on the conditions of the PNRR scheme, the study investigates sizing without investment subsidy, whereby a FIT of 0.095 €/kWh is paid, and with 40% subsidy, in which case half the FIT, 0.0475 €/kWh, applies. Details can be found in section 3.3.4. With 8 ha, the size is typical for a local farm. We are limiting the power of the PV system to 1 MWp, which only requires approximately 2 ha, since above that the relative gains

are negligible, and it is questionable whether a farmer would install an even larger system given constraints in the grid connection and financing.

Table 7: CAPEX and OPEX costs for the Bolzano system

Costs	Min	Med	Max	Comment
Size [kW]	20	100	1000	2 ha, ~535 kWp/ha
Price of PV modules [€/kWp]	205,63	205,63	190,94	same area cost as opaque, P scaled down to 400 W
Inverter [€/kWp]	127,35	43,21	28,49	Max: assuming 3 large inverters
Mounting structures and hardware [€/kWp]	256,00	256,00	256,00	Tracker, high-rise system for 10% transmission
Electrical system [€/kWp]	155,00	155,00	170,00	
Site preparation and installation[€/kWp]	400,00	350,00	300,00	
Administrative and Legal [€/kWp]	110,20	110,20	110,20	
OPEX for PV w/o inverter [€/(kWp*a)]	22,58	20,16	19,00	1.8% of CAPEX
OPEX for inverter [€/(kWp*a)]	2,29	0,78	0,51	1.8% of CAPEX
CAPEX costs w/o inverter [€/kWp]	1 126,83	1 076,83	1 027,14	
Total	**1 254,17**	**1 120,04**	**1 055,63**	

4.2.1.On-farm Consumption / FIT

For the case of energy use on the farm in combination with a feed-in tariff, the optimisation favours a PV system with maximal size, given that the limit imposed is 1 MWp. While this value is arbitrary, the results change only marginally when allowing a bigger system, due to the small reduction of costs per kWp in the linear cost model. This is as expected since the LCOE is below the FIT rate for both the subsidized as the non-subsidized case. Not surprisingly, the optimal battery size is small since with the significant feed-in tariff there is no need for delayed grid injection; it is thus sized to support self-consumption only. The smallest non-zero size in the steps of the model is 31.25 kWh, of which 25 kWh would be usable. Small deviations can occur due to errors and discretization in the calculation of the optimisation tool.

Table 8 summarises the results of the optimisation model. The same layout will be used for the subsequent cases. When optimising for self-consumption using the conditions of the PNRR funding scheme, the optimisations for NPV and discounted ROI yield the same parameters in each case, as columns 2 and 3 show. With the maximal system size of 1000 kWp, a self-sufficiency of 93% can be reached. Given the small electricity consumption of the farm, the payback is positive but marginal, both with the FIT (0.095 €/kWh) and no subsidy as with 40% investment subsidy and half the FIT (0.0475 €/kWh). While a payback time of 12 years is reached with the full FIT and no subsidy, halving the FIT takes the payback to a critically long 16 years. The IRR is below expectations in both cases, and the investment would only be viable due to the low equity share.

Figure 9 outlines the dependence of results on the scaling parameters across all trial runs of the optimisation. In the top chart, the discounted ROI as a percentage of CAPEX is plotted as a function of the rated PV power, indicating that larger systems provide a better return. The size of the symbols shows the battery capacity. The colour indicates the IRR, which closely follows the ROI, with dark blue indicating the optimum and yellow

standing for lower values. The same indicators are used for the bottom chart which shows the NPV as a function of CAPEX. Notably, since the PV size is capped, higher CAPEX than €1.072 M only leads to the installation of more battery capacity, which is not economically beneficial. However, the analysis shows that these systems are economically beneficial over a large range of parameters, and external criteria (peak shaving, additional appliances, security of supply, financial and connection constraints etc.) may lead to different choices in specific cases. The size of the actual demonstrator, 70 kWp, would yield a moderate dROI of about 60% and would be financially viable, but marginal, given the cost scaling assumptions of the study.

Table 8: Parameters of the optimisation study for the Bolzano system, on-farm self-consumption and combined with a fruit cooperative and an energy community, with and without subsidy.

Cat.	Location	Bolzano				
Boundary conditions	Utilisation	Self-consumption 8 ha apple/wine farm		Fruit cooperative + 8 ha apple/wine farm		Energy community + farm with irrigation
	Grid remuneration	FIT	FIT * 1/2	Wholesale	Wholesale	Wholesale
	Financial terms	no subsidy	40% investment subsidy	no subsidy	40% investment subsidy	no subsidy
	Optimisation goal	NPV & ROI	NPV & ROI	NPV & ROI	NPV & ROI	NPV & ROI
	Energy consumption, farm [kWh/a]	7 497		10 672		12 622
	Energy consumption, other [kWh/a]	n/a	n/a	5 097 990	5 097 990	644 524
	Max. PV size (kWp)	1 000		1 000		1 000
	Max. battery capacity (kWh)	1 000		1 000		1 000
PV yield	Specific energy yield (kWh/kWp)	1 724	1 724	1 724	1 724	1 724
	Capacity factor DC	0,197	0,197	0,197	0,197	0,197
Sizing	Size of PV system (kWp)	1000	1000	1000	1000	1000
	Battery rated capacity (kWh)	31,25	31,25	31,25	31,25	31,25
	Size of hybrid inverter (kW)	7497	7497	10672	10672	10672
	CAPEX net [k€]	1 072	643	1 072	643	1 072
El. res.	Total production (kWh/a)	1 724 143	1 724 143	1 724 143	1 724 143	1 724 143
	self-consumption (%)	0,40	0,40	42,50	42,50	11,40
	self-sufficiency (%)	92,9	92,9	14,2	14,2	30,0
Financial results	LCOE DC net (€/kWh)	0,069	0,047	0,041	0,029	0,069
	NPV (k€)	1 020	279	1 393	1 799	1 158
	ROI discounted (%)	95,2	43,3	130,0	279,7	108,0
	Equity PBP (years)	4	9	3	2	4
	Equity IRR (%)	33,1	17,3	44,3	94,4	37,2
	Project PBP (years)	12	16	10	6	12
	Project IRR (%, net CAPEX)	6,6	3,5	8,9	18,9	7,4

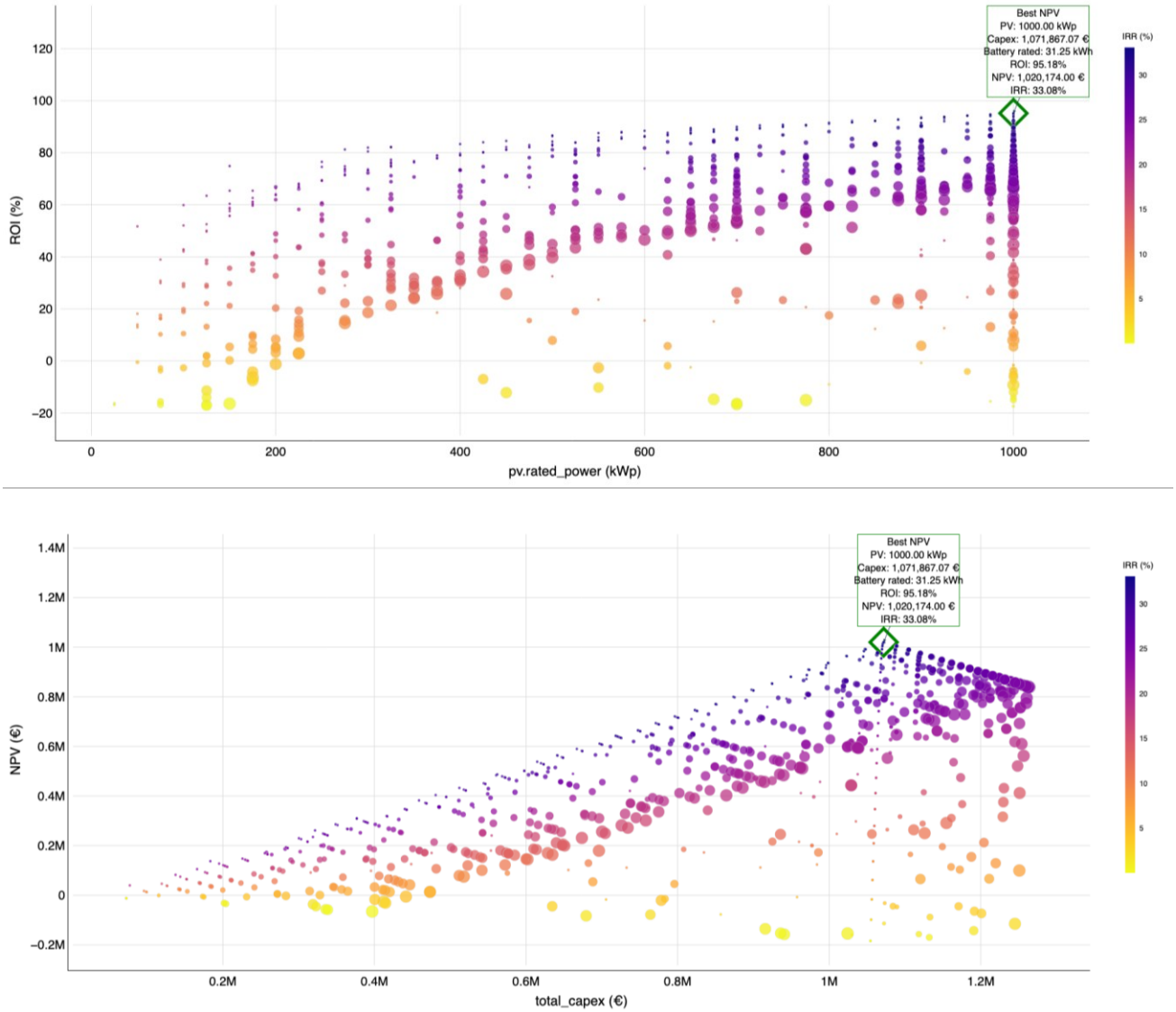


Figure 9: Top: Discounted ROI as a function of rated power of the PV system for the Bolzano farm with self-consumption and FIT. Bottom: NPV as a function of the CAPEX for the same dataset. The colour of the symbols indicates the IRR (darker = better) while their size indicates the battery capacity.

4.2.2. Beyond the Farm: Fruit Cooperative

The picture changes considerably when the energy consumption is enlarged to that of a fruit cooperative in the area near the farm as outlined in section 2.7.2, with the results shown in the following columns 4 and 5 of Table 8. Given the large energy consumption, just over 42% of the produced electricity can be used directly in the cooperative, despite the fact that the cooperative already operates its own PV systems and batteries. Thereby, the PV system supplies approximately 14% of the remaining energy needs. For the financial analysis, we are considering two cases: without investment subsidies, and with a 40% subsidy as it was granted by the PNRR. This is assuming that the exchange is established through an energy community and that the energy shared with the cooperative is remunerated through a share of the subsidies of the TCEC of €0.03/kWh, whereas the excess energy is sold to the grid at the hourly market price, PZO. It should be noted that no

administrative costs are added here; they may subtract from the earnings but are expected to be marginal. Under these assumptions, the system is already financially viable without subsidies, yielding an IRR of 8.9% and a payback time of 10 years. The CAPEX subsidy improves the results to 18.9% and 6 years, respectively.

The sizing is unchanged between the two cases, again resulting in a maximal PV system size and a minimal non-zero battery size. As Figure 10 shows, the NPV has a near-linear dependence on the CAPEX, indicating that a wide range of PV sizes would be viable. It also shows that larger batteries would lead to moderately lower NPV at increase CAPEX, whereby this ratio is critically dependent on the parameters, and larger batteries could become viable with lower prices or a higher share of the subsidies going to the farmer.

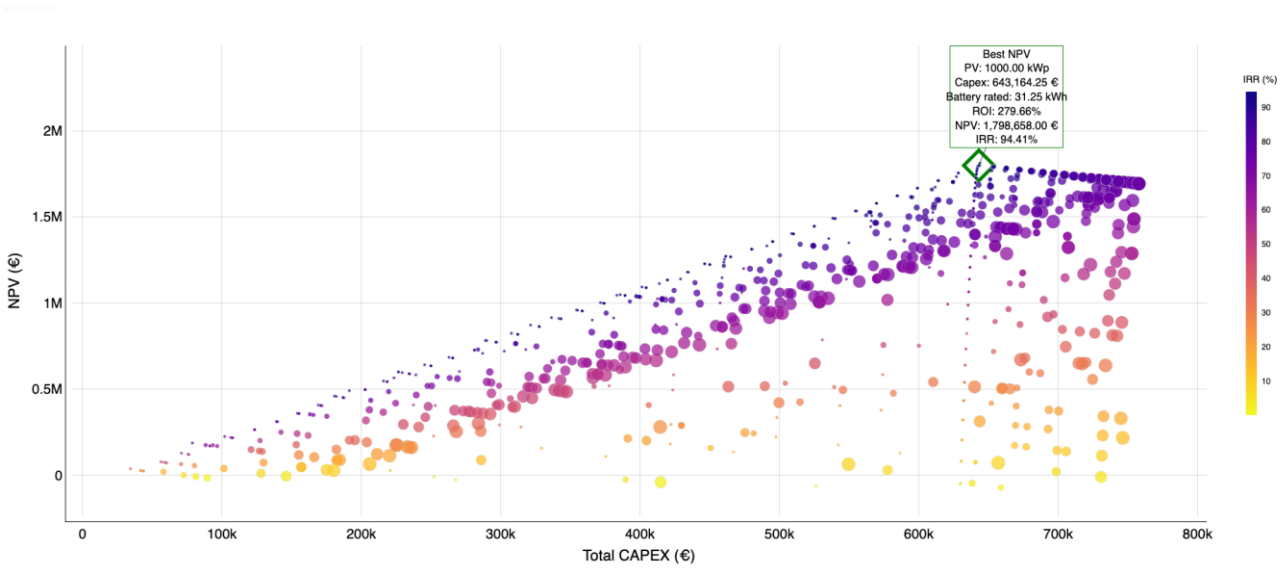


Figure 10: NPV for the Bolzano fruit cooperative as a function of CAPEX. The colour of the symbols indicates the IRR (darker = better) while their size indicates the battery capacity.

4.2.3. Energy Community

As another option to valorise the energy generated by a larger PV system on a farm, an energy-community is considered, whereby we are analysing the case from the perspective of the agri-PV farmer, treated as the sole investor. Detailed assumptions are listed in section 2.7.3. The selected investor farm has a relatively small annual demand of about 10.7 MWh/a, while the optimized PV system reaches the imposed upper bound of 1000 kWp and produces about 1.72 GWh/a. As a result, the system has low physical self-consumption, around 0.4%, and most PV electricity is exported to the grid and remunerated at the hourly PZO price. The virtual EC mechanism increases the investor revenue by remunerating the part of exported PV that is simultaneously consumed by other EC members. As in the case with the fruit cooperative, we are assuming that the owner of the PV system receives €0.03/kWh as a compensation; further earnings go to the EC.

Detailed results can be found in the rightmost column of Table 8: Parameters of the optimisation study for the Bolzano system, on-farm self-consumption and combined with a fruit cooperative and an energy community, with and without subsidy. Table 8. In this optimized case, about 187 MWh/a of exported PV is virtually shared within the EC, corresponding to 29% of the other EC members' annual demand and 11% of the farmer's exported electricity. At €0.03/kWh, this gives an additional EC bonus of about €5.600/year. The resulting financial KPIs are positive, with NPV around 1.16 M€, dROI (discounted ROI) around 108%, IRR around 7.4%,

and payback around 12 years. However, the profitability is mainly driven by PZO export revenue rather than by the EC bonus itself. A slightly higher bonus would greatly improve the business case.

Table 9: Parameters for the optimisation of an orchard farm with the SBB headquarters as energy consumer

Cat.	Location	Bolzano			
Boundary conditions	Utilisation	SBB Headquarter / farm		5xSBB Headquarter / farm	
	Grid remuneration	Wholesale	Wholesale	Wholesale	Wholesale
	Financial terms	PPA €0.10/kWh with HQ	PPA €0.10/kWh with HQ	PPA €0.10/kWh with HQ	PPA €0.10/kWh with HQ
	Optimisation goal	NPV	ROI	NPV	ROI
	Energy consumption, farm [kWh/a]	10 672		10 672	
	Energy consumption, HQ [kWh/a]	215 183		1 075 915	
	Max. PV size (kWp)	1 000		1 000	
	Max. battery capacity (kWh)	1 000		1 000	
PV yield	Specific energy yield (kWh/kWp)	1 724	1 724	1 724	1 724
	Capacity factor DC	0,197	0,197	0,197	0,197
Sizing	Size of PV system (kWp)	975	75	1000	225
	Battery rated capacity (kWh)	31,25	31,25	31,25	31,25
	Size of hybrid inverter (kW)	10672	10672	10672	10672
	CAPEX net [k€]	1 048	104	1 073	266
El. res.	Total production (kWh/a)	1 681 039	129 310	1 724 143	387 932
	self-consumption (%)	8,29	68,26	32,39	80,11
	self-sufficiency (%)	61,7	39,1	51,4	28,6
Financial results	LCOE DC net (€/kWh)	0,069	0,069	0,041	0,043
	NPV (k€)	1 235	182	1 885	674
	ROI discounted (%)	117,9	174,6	175,7	253,0
	Equity PBP (years)	3	2	2	2
	Equity IRR (%)	40,4	59,1	59,4	85,4
	Project PBP (years)	11	8	9	6
	Project IRR (%, net CAPEX)	8,1	11,8	11,9	17,1

4.2.4.Headquarters of SBB

As a next interesting case, we analysed the combination of an Agri-PV farm with the headquarters of our project partner SBB who provided the consumption data, see section 2.7.1. Here, it is assumed that SBB would remunerate the consumed electricity with €0.10/kWh while the excess is sold to the grid at PZO. Additionally, we investigated the effectiveness when the same scheme would be extended to more, similar consumers by multiplying the consumption by five. Table 9 summarises the results. In both cases, the optimisation for NPV and for dROI results in different system sizes. As the second column shows, a near-maximal size is chosen for best NPV, yielding a payback period of 11 years and an IRR of 8.1%. For best ROI, a much smaller system of only 75 kWp is chosen, bringing the PBP to 8 years and the dROI to 11.8%. Figure 11 shows the underlying dependency of ROI on size: While smaller systems improve the return, the entire range of sizes is effectively viable. However, since the goal is self-supply, and there are additional gains on the side of SBB, a maximal ROI

should not be the main goal. Batteries yield no positive effect – probably because a large share of the energy consumption of an office building takes place during daytime.

While the larger system can supply about 62% of the headquarters' consumption, just over 8% of the generated electricity are consumed by it and the farm as Table 9 shows, and the IRR improves to 11.9%. Again, as column 5 shows, a smaller system would still yield a better ROI, but the optimal size has multiplied by a factor of three.

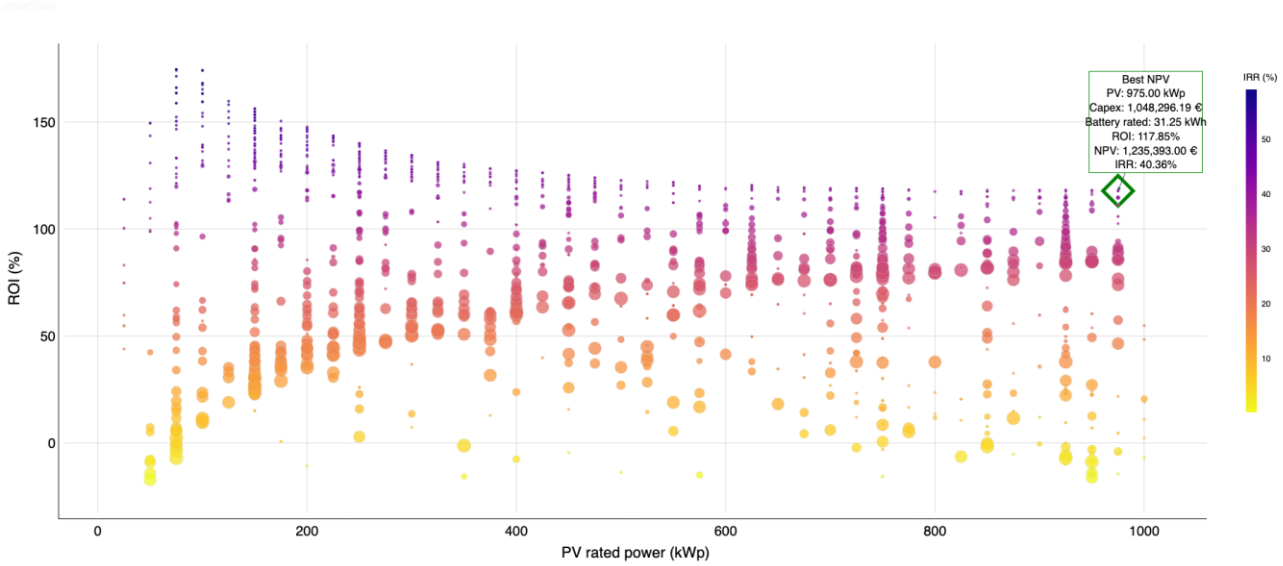


Figure 11: dROI as a function of PV system size for the combination of agri-PV farm with the headquarters.

4.3. Open Agri-PV - Scalea Citrus Orchard

The Scalea use case represents an open Agri-PV system for a citrus orchard in Southern Italy, designed around a traditional 3D tree configuration and a strong self-consumption logic. The demonstrator system is off-grid and resistors are used for dissipation of the electrical energy to simulate a load. According to the proposal, part of the generated PV electricity is intended to be used directly on site for electrically powered cultivation equipment, including tractors, pumps, compressors, and related auxiliary systems. We are considering these but treat the case as an on-grid one, since an off-grid setting would not be economical and on-farm energy use is very limited. As stated earlier, the PV system needed for this would easily fit on a roof. See section 2.7.4 for details of the modelling. The PV system is slightly cheaper than that of Bolzano due to the commercial opaque PV modules used here. The other cost assumptions are kept constant; see Table 10 for details. The model uses simulated hourly energy yield data provided by our partner 3E.

The sizing model is used with FIT and with 40% investment subsidy and a power purchase agreement (PPA) that is realized through a Contract for Difference with a settlement price of €0.06/kWh. If only sales at wholesale prices would be considered, the return would be negative (not shown). The differences between the cases are very limited. It maximises the size of the PV system in both cases and minimises the battery size. The best return on investment is reached with the full FIT, yielding a sufficient IRR of 9.1% and a payback period of 9 years, see Table 11. The case with investment subsidy yields a slightly lower return with a lower net investment, taking the payback time to 10 years and the IRR to 8.8%.

Table 10: CAPEX and OPEX costs for the Scalea system

Costs [€/kWp]	Min	Med	Max	Comment
Size [kW]	20	100	2300	max. 3 ha, ~769 kwp/ha
Price of PV modules [€/kWp]	218,75	212,50	198,75	Standard modules 545 W, opaque
Inverter [€/kWp]	127,35	43,21	24,92	
Mounting structures and hardware [€/kWp]	230,00	230,00	230,00	Tracker, high-rise system
Electrical system	155,00	155,00	170,00	
Site preparation and installation	400,00	350,00	300,00	
Administrative and Legal	110,20	110,20	110,20	
OPEX for PV w/o inverter [€/(kWp*a)]	22,34	19,82	18,61	1.8% of CAPEX
OPEX for inverter [€/(kWp*a)]	2,29	0,78	0,45	1.8% of CAPEX
CAPEX costs w/o inverter [€/kWp]	1 113,95	1 057,70	1 008,95	
Total	**1 241,30**	**1 100,91**	**1 033,87**	

4.4. Open Agri-PV - Barcelona Lettuce Farm

The Barcelona use case (Agrivoltopolis) represents a vegetable production system with relatively low crop height and a more flexible operational structure. The demonstration system which the calculation is based on consists of 70 PV modules each with 10% and 40% transparency. They have a nominal power of 395 Wp and 274 Wp, respectively, and form a system with a total nominal power of 47.7 kWp. Since the row spacing for the module types is 5.9 m respectively 4.1 m, they have near-identical power densities per surface area of 527 kWp/ha and 526 kWp/ha.

The Agri-PV installation is designed to support irrigation, as well as the electrification of tools, vehicles, and potentially automated systems. The data provided by our partner UPC mainly describe the physical system and intended energy uses, including irrigation and future integration of electrically powered equipment. As with the other open-field use cases, no direct high-resolution consumption data was available. To construct the load profiles, irrigation was considered as the primary energy demand, supplemented by additional loads related to machinery and potential automation. Compared to orchard systems, vegetable production allows for more flexibility in operation, which was reflected in the assumed temporal distribution of loads.

Typical lettuce farms are small, wherefore a size of 2 ha is used here. As before, 1 MWp is used as the maximum size, which would fill approximately the entire agricultural area; above that per-kW costs would only decrease very gradually. Compared to the cases of orchards, a lower minimal system height of 2.1 m is assumed, leading to lower installation costs, while the other BOS costs are kept the same. The study uses modules with a transparency of 10%. This leads to overall installed costs of €1 196 for a size of 20 kWp, €1 062 for 100 kWp, and €998 for the maximal size of 1 000 kWp, as Table 12 shows.

Table 11: Parameters of the optimisation study for the Scalea system, on-farm self-consumption with FIT without subsidy and with the combination of CAPEX subsidy and fixed-price PPA.

Cat.	Location	Scalea	
Boundary conditions	Utilisation	Self-consumption, 3 ha citrus farm	
	Grid remuneration	FIT	PPA
	Financial terms	no subsidy	40% investment subsidy
	Optimisation goal	NPV & ROI	NPV & ROI
	Energy consumption, farm [kWh/a]	5 265	
	Energy consumption, other [kWh/a]	n/a	
	Max. PV size (kWp)	2 300	
	Max. battery capacity (kWh)	500	
PV yield	Specific energy yield (kWh/kWp)	1 987	1 987
	Capacity factor DC	0,227	0,227
Sizing	Size of PV system (kWp)	2300	2300
	Battery rated capacity (kWh)	31,25	31,25
	Size of hybrid inverter (kW)	5265	5265
	CAPEX net [k€]	2 398	1 438
El. res.	Total production (kWh/a)	4 569 599	4 569 599
	self-consumption (%)	0,11	0,11
	self-sufficiency (%)	97,0	97,0
Financial results	LCOE DC net (€/kWh)	0,059	0,040
	NPV (k€)	3 206	1 862
	ROI discounted (%)	133,7	129,5
	Equity PBP (years)	3	3
	Equity IRR (%)	45,5	44,1
	Project PBP (years)	9	10
	Project IRR (%, net CAPEX)	9,1	8,8

4.4.1.On-farm consumption

The main difference to the cases in Italy is that no FIT exists in Spain, and sales to the grid are remunerated at market price only. Therefore, any case that mainly targets grid injection yields financial losses, as the second column of Table 13 shows. Without subsidies, an optimisation for NPV thus results in a very small system, whereby this study uses 20 kWp as the minimum with which a self-sufficiency of 85% would already be reached while only 4% of the electricity would be used on the farm itself. Here, ROI optimisation would suggest a larger size, but also a negative result – as shown in column 3 just for completeness. At this scale, it is questionable whether an Agri-PV system would be installed anyway, since enough PV modules could typically be placed on a roof of a farm, which tends to be the cheaper solution. When 40% of the CAPEX are granted as subsidy and another 40% are based on a 0.5% loan rate, the optimisation model maximises the system size, and reasonable payback times of 7 years for equity and 13 years for the entire investment are reached. See the fourth column of Table 13 for details. Given the low on-farm energy demand, a small battery is chosen. It supports the self-consumption, but there is no chance that a battery would pay back from the differences in

wholesale prices at different times of injection. It should be noted that projects are only eligible for subsidies if they are recognized as "innovative", which can apply to Agri-PV, then with the obligation to record data, or if they are larger than 5 MWp, which is beyond the scope of the present study given the limited farm sizes.

Table 12: CAPEX and OPEX costs for the Barcelona system

Costs	Min	Med	Max	Comment
Size [kW]	20	100	1000	2 ha, max. ~629 kWp/ha
Price of PV modules [€/kWp]	205,63	205,63	190,94	same area cost as opaque, P scaled down to 400 W
Inverter [€/kWp]	127,35	43,21	28,49	Max: assuming 3 large inverters
Mounting structures and hardware [€/kWp]	198,00	198,00	198,00	Tracker, low-rise system
Electrical system [€/kWp]	155,00	155,00	170,00	
Site preparation and installation[€/kWp]	400,00	350,00	300,00	
Administrative and Legal [€/kWp]	110,20	110,20	110,20	
OPEX for PV w/o inverter [€/(kWp*a)]	21,53	19,12	17,96	1.8% of CAPEX
OPEX for inverter [€/(kWp*a)]	2,29	0,78	0,51	1.8% of CAPEX
CAPEX costs w/o inverter [€/kWp]	1 068,83	1 018,83	969,14	
Total	**1 196,17**	**1 062,04**	**997,63**	

4.4.2.Agri-PV with Local Energy Community

The results change drastically when the combination with an energy community is considered. Contrary to the case of Bolzano, a real community nearby a farm was not available, although they are a proven concept in Spain. Therefore, we constructed a hypothetical case with one farm and 200 households as outlined in section 3.4.4. The study focuses on investment subsidies as the means of support – other schemes like the monthly net compensation of grid injected energy without fees would require detailed simulations of energy flows and related fees of the individual constituents that are beyond the scope of this analysis.

The main effect is the supplanting of energy costs of the LEC, since the average purchase price is €0.155/kWh, while the pre-tax LCOE amounts to €0.051/kWh. See columns 5 and 6 of Table 13, respectively, for details. The parametric optimisation with a maximum of 1 200 kWp yields an optimal PV system size of 945 kWp. The substantial price difference supports the use of a sizeable battery with a capacity of 375 kWh, even if no subsidies are granted. In this case, the payback time is prohibitively long, with 11 years for equity only, and 19 years if the full investment amount is considered, given that there are technical and market risks involved. The project pre-tax IRR of 3% is marginal. It is thus questionable whether such a project would be realized, unless additional advantages would come into play. Investment subsidies can amount to between 30% and 50%. We are assuming a 40% investment subsidy for comparability with the cases in Italy. Additionally, a subsidized interest rate of 0.5% is offered in Spain for max. 40% of the investment volume, i.e. the total minus the 40% subsidy and 20% equity (see section 3.4.6). The optimisation model suggests maximising the PV size and choosing a slightly larger battery with 406 kWh capacity. The pre-tax IRR increases to 10% while the payback period reduces to 10 years, making this an attractive investment. The self-sufficiency of the entire community reaches 61% without, or 62% with subsidies, indicating that in either case the PV system is sized appropriately

for the size of the LEC. In the subsidized case, the uptake of the LEC is constant in combination with a larger PV system – the lower self-consumption shows that the added capacity supports higher grid injection rather than more energy use within the LEC, even though a larger battery is chosen.

Table 13: Parameters of the optimisation study for the Barcelona system, on-farm consumption and grid injection and combined with an energy community, with and without subsidy.

Cat.	Location	Barcelona				
Boundary conditions	Utilisation	Self-consumption, 2 ha lettuce farm			Energy community, 2 ha lettuce farm + 200 households	
	Grid remuneration	Market price		Market price	Market price	Market price
	Financial terms	no subsidy		40% investment subsidy + low interest loan	no subsidy	40% investment subsidy + low interest loan
	Optimisation goal	NPV	ROI	NPV & ROI	NPV	NPV
	Energy consumption, farm [kWh/a]	2 118			4 237	
	Energy consumption, other [kWh/a]	n/a			521 416	
	Max. PV size (kWp)	1 000			1 200	
	Max. battery capacity (kWh)	200			1 000	
PV yield	Specific energy yield (kWh/kWp)	2 130	2 130	2 130	2 130	2 130
	Capacity factor DC	0,243	0,243	0,243	0,243	0,243
Sizing	Size of PV system (kWp)	20	1000	1000	945	1195
	Battery rated capacity (kWh)	12,5	12,5	12,5	375	406,25
	Size of hybrid inverter (kW)	4237	4237	4237	4237	4237
	CAPEX net [k€]	31	1 002	602	1 105	815
El. res.	Total production (kWh/a)	42 601	2 130 098	2 130 098	2 012 943	2 545 467
	self-consumption (%)	4,23	0,10	0,10	15,83	12,81
	self-sufficiency (%)	85,0	95,8	95,8	60,6	62,0
Financial results	LCOE DC net (€/kWh)	0,057	0,053	0,029	0,051	0,027
	NPV (k€)	-6	-36	425	404	999
	ROI discounted (%)	-20,1	-3,5	70,6	36,6	122,6
	Equity PBP (years)	null	null	7	11	4
	Equity IRR (%)	-0,8	4,0	20,2	15,3	30,7
	Project PBP (years)	null	null	13	19	10
	Project IRR (%, net CAPEX)	-0,2	0,8	6,7	3,1	10,2

As Figure 12 shows, there is a weak dependence of NPV on battery capacity. Larger batteries, which would increase the self-consumption further, would reduce the NPV, but would be financially viable. Similar to the Bolzano case, optimisation for best IRR or ROI would result in much smaller PV system sizes. These results are disregarded, since the point of an energy community is to supply the consumers with as much electricity as possible, and this can be done with positive NPV across a wide range of system sizes. The true limit will probably be imposed by the grid connection in any case.

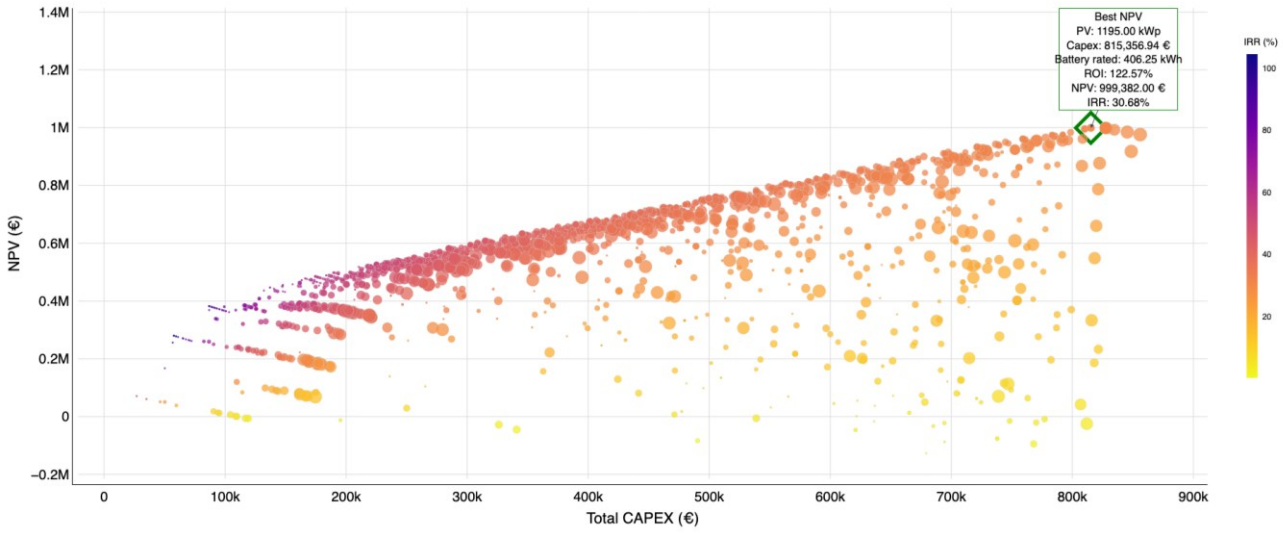


Figure 12: NPV for the Barcelona energy community with investment subsidies as a function of CAPEX. The colour of the symbols indicates the IRR (darker = better) while their size indicates the battery capacity.

4.5. Closed Agri-PV – Mons, Belgium

Form the new project partner, Green City Wallonie (GCW), we received data from their greenhouse in Mons that is installed on a farm site that also has a restaurant, Le Cour de Dames. The corresponding consumption makes this an interesting case. The greenhouse is equipped with a PV system with 156 modules with a nominal power of 88 kWp, with orientations of northeast and southwest at a fairly shallow slope. They are connected to two inverters of 20 kW each which are combined with an AC battery of approximately 600 kWh. During 292 days of which data were available, the energy flows were recorded and scaled to a full year. See Figure 13for the obtained daily values. No seasonal correction was attempted – there is a relatively long data gap of 33 days in summer and an even longer one of 103 days in winter and spring, as well as smaller gaps. For a year, this amounts to a generated energy of 82 525 kWh, consumed energy of 45 820 kWh and purchased energy of 14 770 kWh. Out of this energy, 16 521 kWh were routed through the battery. Thus, 38.4% of the generated PV energy were self-consumed, and 67.7% of the consumed energy were supplied by the PV system. Owing to the ongoing onboarding of the partners, we cannot present a cost analysis at the time of this Deliverable. Given that standard PV modules were attached to a structure that is needed for other purposes, thus lowering the CAPEX, and the rather high electricity purchase costs in Belgium, this should present a very good economic case.

4.6. Italian tender as reference

According to Italy's Ministry of the Environment and Energy Security (MASE), 747 projects have been selected under the nation's first agrivoltaics program [31] that was offered starting in 2024 and extending into 2025, with a set ceiling price of €0.093/kWh for projects up to 300 kW and €0.085/kWh for larger installations. Of the selected projects, 363 exceed 1 MW, representing a combined capacity of 1.76 GW and requiring a total budget of €957.1 million. Another 384 smaller projects under 1 MW will add 253 MW at a cost of €141.8 million. They will receive subsidies covering up to 40% of eligible costs, along with a guaranteed purchase price for net electricity supplied to the grid. The vast majority of these systems will be installed in the south of Italy owing to the higher insolation.

An earlier publication of a subset of this tender shows that projects with less than 1 MW of capacity came in at an average price of €0.0889/kWh and accounted for a combined 178 MW of capacity, while projects larger than 1 MW, averaging 5 MW in size, showed a price of €0.0799/kWh [32]. These prices are based on the project planning, i.e. including the calculated margin of the investor. The realization is foreseen to take place latest in June 2026, after postponement from an earlier deadline.

These figures can serve as a reference for the calculations of this study. Firstly, the tender shows a clear trend to larger systems, indicating that the systems with sizes below 1 MWp have an average size of 659 kWp, not dissimilar to the findings in this study. This is clearly much larger than anything that would primarily target self-consumption and is driven by investors making their inroads into Agri-PV. The average calculated all-in offering of the investors including subsidies, fees, taxes and revenues amounts to €1 401/kWp. With a simple cashflow model, using the background data from the Scalea system, the projects yield an approximate IRR of 5% and a payback period around 13 years, which would extend to 20 years if no subsidies were granted. This is very comparable with the Scalea case with investment subsidy above.

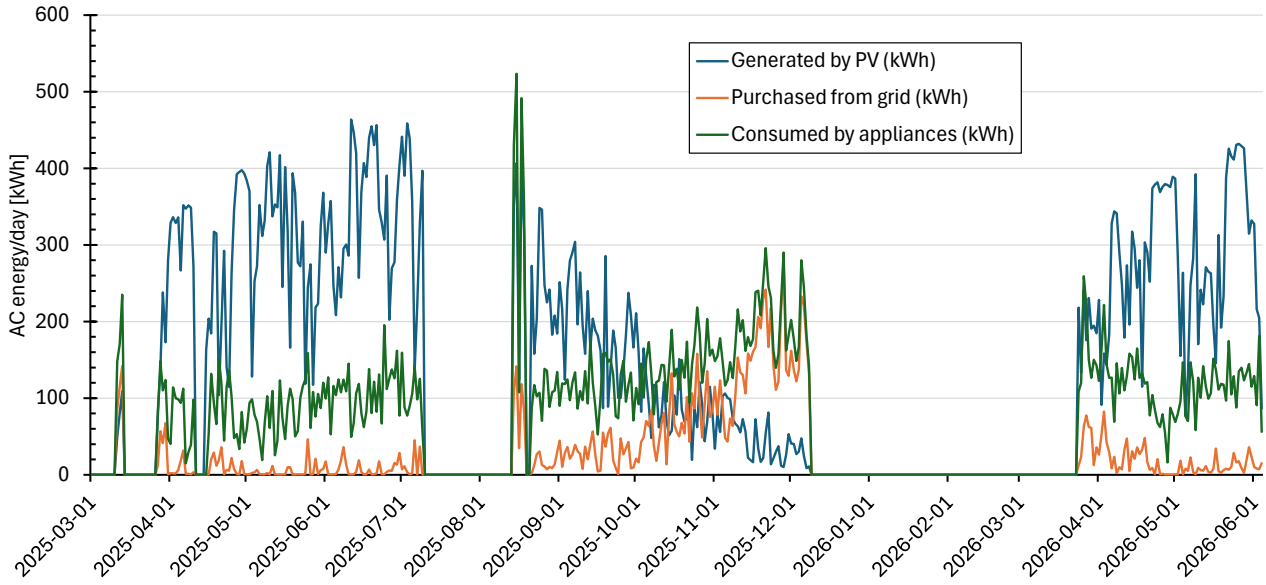


Figure 13: Time profiles of generation, purchase and consumption for the Mons site for the period March 2025 to May 2026.

4.7. Summary and Discussion of Results

Generally, Agri-PV systems are found to be economically viable if they are connected to a sufficiently large set of consumers, offsetting a larger share of their purchase costs, or if a sufficient subsidy is granted. The asset sizing study suggests a maximisation of the size of the PV system in all cases where a net benefit can be obtained. Its findings are summarised in Table 14. “FIT * ½ ” refers to the fact that under PNRR in Italy only half the FIT (€0.0475/kWh instead of €0.095/kWh) is paid when an investment subsidy of 40% of the CAPEX is provided. “Low interest loan” means that in Spain a loan with a 0.5% interest rate with a tenor of ~15 years can be obtained under the IDAE programme.

Table 14: Schematic overview of results of the asset sizing study.

System, Location	Energy use	Sales & subsidy	Financial viability	PV sizing optimum	Battery sizing optimum
Open, Bolzano (IT), apple / wine farm	On farm	FIT, no subsidy	yes	Maximum	Minimum
		FIT * ½, CAPEX subsidy 40%	unlikely		
	Fruit cooperative	Wholesale price, no subsidy	yes		
		Wholesale price, CAPEX subsidy 40%	**yes**		
	Energy community	Wholesale price, no subsidy	yes		
	Headquarter offices	Wholesale price & PPA, no subsidy	yes	NPV: max, ROI: small	
	More office buildings	Wholesale price & PPA, no subsidy	**yes**	NPV: max, ROI: medium	
Open, Scalea (IT), citrus orchard	On farm	FIT, no subsidy	yes	Maximum	Minimum
		PPA, CAPEX subsidy 40%	yes		
Open, Barcelona (ES), lettuce farm	On farm	Market price, no subsidy	**no**	(Minimum)	Minimum
		Market price, CAPEX subsidy 40%, low interest loan	marginal	Maximum	
	Energy community	Market price, no subsidy	**no**	(Medium)	(Medium)
		Market price, CAPEX subsidy 40%, low interest loan	yes	Maximum	**Medium**

The battery size is kept to a minimum where a FIT is granted, owing to the time-independence of injection, or where the financing is critical. It is thus only scaled towards the self-consumed energy. Only in cases of large consumption of an energy community, there is a sufficient payback for larger batteries, and only if an investment subsidy is granted. The cost/benefit significance of the battery sizing is marginal; the optimal size is thus critically dependent on the boundary conditions and pricing. An indication for this is that the optimal battery size is minimal for the fruit cooperative, and medium for the energy community, whose consumption is only higher by a small amount. Even in this case, the optimal battery is very small compared to the PV system, probably owing to the given correlation between capacity and price. Larger batteries are feasible and would increase self-sufficiency and to a degree also self-consumption; their implementation would be made more attractive if additional remuneration could be gained from grid support and sales of flexibility. These aspects are left out of the present study.

4.8. Key Dependencies

The analysis presented here aimed at exploring which cases of agri-PV systems are viable with the types of settings given by the pilot installations. The assumptions on the boundary conditions are not easily generalised, and several parameters are difficult to estimate. This concerns in particular the ground preparation and grid connection costs, but also insurance and taxation. The granularity of the optimisation model and the necessary interpolation are not necessarily warranting exact dimensioning. We are also assuming a quite moderate interest rate of 4% and an equity share of only 20%. The partners in this task take the liberty to start from the side of optimism in order to not disregard any potential cases. Every single potential installation will have to be analysed in detail for true costs and potential complications; this is beyond the scope of the current study.

Contrary to assumptions at the time of the planning of this project, agri-PV systems tend to larger sizes and are more driven by investors, as evidenced by the recent tender in Italy. Self-supply of the farm has thus become a less important factor in the planning. We therefore analysed systems with a broad range of sizes, and it can be observed that, apart from pathological cases, larger PV systems generate a better payback. Obviously, this sort of optimisation will find its boundaries in the financial capabilities of the investors, but also in the connection capacity of the local electricity grid, respectively the willingness of the grid operator to reinforce it. This is another highly local matter which particularly affects also energy communities, since it eventually constrains their size, interesting as the concept is for the utilisation of PV electricity and the supply of households and SMEs. Management of distributed electricity generation and storage will therefore become an important aspect of planning as a joint exercise, and batteries will gain value if they contribute to limiting grid loads and avoiding costly expansions.

5. Conclusions and Recommendations

It is not easy to gain accuracy on many parameters that enter into a study as the present one on all fronts. This already applies to present costs and revenues, grid loads etc. Further to that, the evolution of grid prices, both on the sales as on the purchasing side, is uncertain. Feed-in tariffs are stable once they are granted, usually for 20 years, but their further existence is questionable since solar power tends to inject most at times of high generation, complicating grid stabilisation and leading to frequent curtailment. This work is based on modelling of the pilot installations based on an optimisation for energy yield, while some adaptation to improve crop yield may be necessary, and yield figures may need to be revised based on measured data. It can be observed that battery sizes beyond the minimum needed for self-consumption is cost-prohibitive by a small margin. Cheaper batteries or increases in the difference between generation and injection price could enable larger batteries, which would allow to increase the self-consumption and self-sufficiency.

The present work should thus only be considered as an assessment where Agri-PV is applicable in principle, and under which boundary conditions. It is not to be read as an advice how to design an Agri-PV system for a specific farm, or as a statement that a specific combination of installation and use case is, or is not, profitable. Variables in each parameter both on the generation and cost sides can lead to vastly different financial outcomes. Constraints on permitting, tendering and grid connection are weighing in as well.

Summarising the cases, we find that Agri-PV installations in Italy are viable if a sufficient feed-in tariff is granted, and/or investment subsidies are provided as was the case in the PNRR tendering scheme which has now come to an end. Also, the market price is relatively high, improving the payback on PV for self-sufficiency. The rules on energy communities make such collaborations very interesting. We have thus analysed systems

in the Bolzano and Scalea areas based on the conditions of PNRR to establish a base case and have compared the latter to the recent Agri-PV tender in Italy to validate our cost assumptions. From the present study, it appears that a similar subsidy scheme, if with adaptations to the pay scale, is essential for the further roll-out of Agri-PV, as far as Agri-PV on farms with the goal of grid injection is concerned. The investment subsidy has the advantage of lowering the entry barrier, while a FIT ensures continued revenues over the lifetime.

Agri-PV is definitely interesting to consider when it can be combined with sizeable nearby consumers. In this study, three cases in the Bolzano area, Italy, were investigated:

a) The combination of an Agri-PV farm with the headquarters of our project partner SBB which is viable given a sufficiently high clearance price of a PPA and the relatively high market prices of Italy. It benefits from the fact that most of the consumption of the offices takes place during daytime, with some baseload during the remaining hours.
b) A fruit cooperative in the area, which turns out to be able to absorb electricity at a profitable rate despite the fact that it already owns PV systems and storage batteries.
c) An energy community, for which the electricity is routed through the regular grid, and its producer receives a compensation based on the electricity consumed within it, with the remainder being paid at regular wholesale price. This is feasible as long as the members are located in the range of the same substation; we constructed a case with 200 households and 13 farms (dairy and apple/wine) based on available consumption profiles.

If no feed-in tariff is given, and no subsidy granted, Agri-PV systems are not viable financially, as the Barcelona case shows. In Spain, the buying price for electricity is also lower, reducing revenues on the self-consumed energy as well. With a 40% subsidy, marginal payback is reached. What makes the installation interesting is the combination with an energy community, although even there, subsidies are nearly a requirement, given the market conditions characterized by low purchase price and only wholesale remuneration for excess electricity injected into the grid. We have resorted to a generic dataset to test this opportunity with some arbitrary numbers of households, finding a good combination with 200 of them and a 2 ha lettuce farm. The big question regarding realisation is again the capacity of grid connections, and whether such a set of prosumer and consumers can be located within the range of an electrical substation.

In the case of the closed Agri-PV system on greenhouses in Mons, Belgium, we can so far only state that the combination of the PV generation with the farm and a restaurant on site leads to a high degree of self-consumption. An economic analysis cannot be presented at this point.

The resilience funds that some subsidies depended on, especially PNRR in Italy, are coming to an end, and it remains to be seen if sufficient continued support will be available. Agri-PV presents a great opportunity for the dual use of land instead of dedicating fertile ground to PV systems only. It would be advisable to devise funding schemes that enable the use of the technology in a sensible way with a critical eye on financing. Learning about the actual costs and production will help to tighten the bounds on the investments and to come to better bankability. Further to that, contracts on flexibility and grid support could enhance the economic case, especially for larger batteries. These are expected to become more commonplace in the future.

Work on quantifying the performance accurately, and de-risking installations, is ongoing in the SYMBIOSYST project, which will help to lower risk margins in the future, helping to make the technology more viable. Further work will focus on determining emission reductions achieved by these installations and link the economic efficacy of the PV systems to the effect on the crops, to come to a refined assessment of viability.

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Annex A: Calculation of irrigation load (Scalea case)

Irrigation pumping

Irrigation is the dominant load and is modelled based on annual water demand and hydraulic energy requirements. Reported irrigation volumes for citrus orchards in Mediterranean conditions are commonly in the order of several thousand cubic metres per hectare per year (e.g., 3,500–5,000 m³/ha·year [https://www.crea.gov.it/en/web/agricoltura-e-ambiente/banche-dati), but these values depend strongly on local climate, rainfall contribution, soil characteristics, tree age, canopy cover, and irrigation system configuration. For this reason, a site-adapted estimation methodology was adopted for the Scalea case study rather than relying on a single generic annual value.

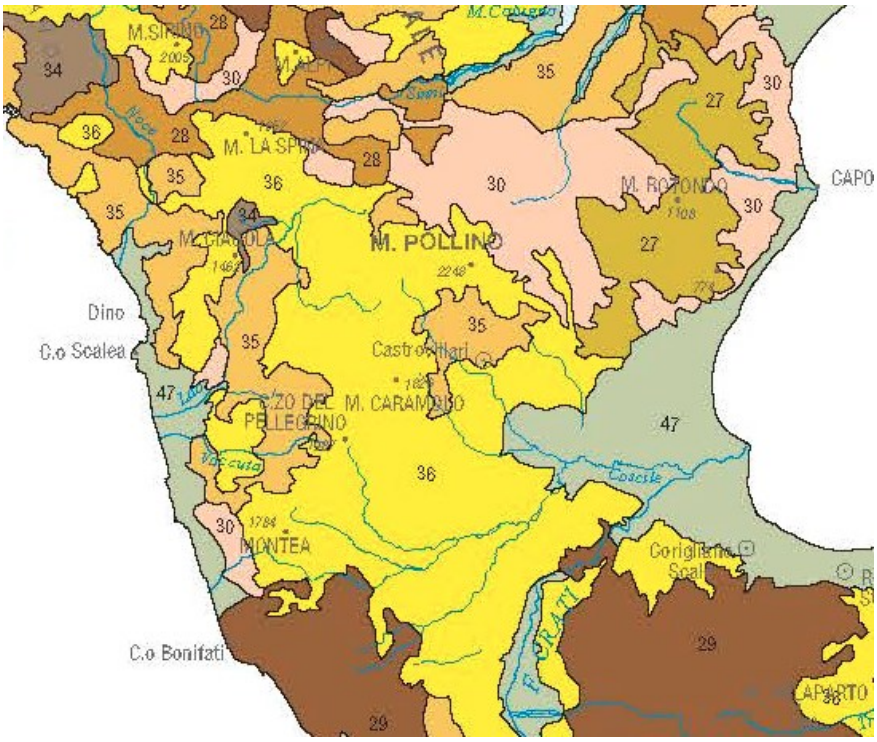
The adopted approach follows the practical citrus irrigation methodology presented by in https://www.safj.co.za/irrigation-of-citrus-trees-a-practical-approach/ , in which the orchard water demand is derived from reference evapotranspiration, crop coefficients, soil water availability and allowable depletion. In this framework, crop evapotranspiration is estimated from reference evapotranspiration (ET_0) and a crop coefficient K_c:

$$ET_c = ET_0 \,.\, K_c$$

The SAFJ paper reports monthly K_c values for citrus under both micro-irrigation and drip irrigation, differentiated by canopy cover. For a representative mid-age orchard with approximately 50% canopy cover under micro-irrigation, the published monthly K_c values are 0.80, 0.70, 0.63, 0.57, 0.51, 0.46, 0.48, 0.48, 0.49, 0.68, 0.87 and 0.95 for July to June, respectively. These coefficients are intended for use together with ET_0 derived from weather data, typically by the Penman–Monteith method.

The second element of the method is the estimation of the soil water buffer that can be depleted before irrigation is triggered. The SAFJ paper defines readily plant-available water as a soil property expressed in mm/m and provides indicative values by texture class. The soil characteristics of the study area are derived from the Carta dei suoli d'Italia – Soil Map of Italy, provided by the European Soil Data Centre (ESDAC) https://esdac.jrc.ec.europa.eu/content/carta-dei-suoli-ditalia-soil-map-italy

As illustrated in Figure ...., the coastal plain in the vicinity of Scalea is predominantly composed of light-textured soils, which can be classified as sandy loam. Based on this classification, the readily plant-available water (RPAW) is selected according to literature values for sandy loam soils which is approximately 125 mm/m.



Carta dei suoli d'Italia - Soil Map of Italy
Resource Type: National Soil Maps (EUDASM)

Assuming an effective citrus rooting depth of 0.4 m, the corresponding readily plant-available water within the root zone is therefore:

$$RPAW_{rz} = 125 \times 0.4 = 50\ mm$$

The same paper further states that allowable depletion is generally around 40% of readily plant-available water for citrus, while for sandy soils this should be reduced to 30%; more detailed limits by phenological stage are also provided, ranging from 30% during flowering and early fruit growth to 40–50% during fruit maturation. For a baseline annual model, a depletion fraction of 40% is retained as a representative value. The corresponding irrigation trigger threshold is therefore:

$$D_{max} = 50 \times 0.40 = 20\ mm$$

In practice, this means that irrigation is applied whenever the accumulated crop water use since the previous irrigation event reaches approximately 20 mm.

The third element is the conversion of this irrigation requirement into an irrigation event volume and operating time. If the net irrigation depth per event is set equal to the allowable depletion, then the net depth is 20 mm. For a micro-irrigation system with an application efficiency of 0.80, the gross applied depth becomes:

$$I_{gross} = \frac{20}{0.80} = 25\ mm$$

Expressed as a water volume, this corresponds to:

$$V = 25 \times 10 = 250\, m^3/ha$$

since 1 mm over 1 ha is equivalent to 10 m^3. To translate this into pump operating time, a representative emitter layout can be assumed. For example, with a planting density of 555 trees/ha (6 m × 3 m spacing), two micro-sprinklers per tree, and 40 L/h per emitter, the system flow rate is:

$$Q = 555 \times 2 \times 40 = 44400\, L/h = 44.4\, m^3/h.ha$$

which is equivalent to an application rate of 4.44 mm/h. Under these assumptions, the irrigation duration per event is:

$$t = \frac{25}{4.44} \approx 5.6\, h$$

This calculation provides the link between agronomic water demand and hourly electrical load from pumping.

The methodology is implemented as a dynamic soil water balance model to generate time-resolved irrigation demand and associated pumping load. Crop evapotranspiration is calculated from reference evapotranspiration and crop coefficients, and the cumulative soil water depletion is tracked over time. When the depletion exceeds the predefined threshold, an irrigation event is triggered.

Each irrigation event corresponds to a fixed water depth, which is converted into a pump operating duration based on the irrigation system application rate. During this period, the irrigation system is assumed to operate continuously, resulting in a corresponding electrical load. By repeating this process over the year, an hourly irrigation pumping profile is obtained, which directly represents the electricity consumption of the irrigation system.

The electrical load associated with irrigation is estimated by assuming a constant pump power of 7.5 kW per hectare during irrigation operation, representing a typical value for micro-irrigation systems. This assumption is consistent with the expected hydraulic power requirements, which depend on the system flow rate, pumping head and pump efficiency, and can be generally expressed as:

$$P = \frac{\rho \cdot g \cdot Q \cdot H}{\eta}$$

where Q is the volumetric flow rate, H is the total dynamic head, η is the pump efficiency, and ρ and g are the water density and gravitational acceleration, respectively. For typical operating conditions of micro-irrigation systems, this results in power requirements in the range of a few kilowatts per hectare, supporting the adopted assumption.