Modeling Scenarios for PV-Powered Agricultural Energy Systems using Seasonally Varying Demand Profiles at Hourly Resolution

Anticipating Decarbonization of Dutch Farm Loads

Tim Kaasjager - 19 August 2024



TU Delft Delft University of Technology

Challenge the future

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by Tim Kaasjager

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Appendix can be requested. Source cover page: solarkeyenergy.com/en/agrivoltaics/

Preface

This report is the final deliverable of the thesis project that I embarked on in November of 2023 with TNO and the PVMD Group. For almost a year, I was welcomed by the Solar Expertise group in Petten to work on something completely new and exciting. During the project, I have experienced both a great degree of freedom as well as a sense of responsibility for inspiring and contributing to new fields of research in the Group's modeling team.

That is why I would like to give special thanks to my daily supervisor at TNO, Bas van Aken. During our first interactions, *he* invested time in getting to know *my goals and interests*, both academically and personally, instead of the other way around. His attitude towards research reflects TNO's human-centered and curiosity-driven approach. It is no wonder that the team consists of such diverse and intrinsically motivated individuals.

Initially, I had two wishes with this project: the first was that I wanted the topic to relate to agrivoltaics. The second wish was that to improve my coding skills. As an added bonus, it would allow me to work remotely, in my home in Amsterdam, for example. When I did visit Petten, it was always a pleasure to meet colleagues from TNO working on wildly different topics, and partaking in the timely lunch and coffee rituals.

I can happily say that these two wishes came in fulfillment. However, along the way, I came to appreciate some unexpected lessons. One is that I found a more balanced work-life balance. A solo project like a thesis forced me to take good care of my mental and physical health, and I have adopted healthier daily and weekly habits.

Someone who I aligned very well on this with is my daily supervisor on behalf of the PVMD Group, Arthur Weeber. Whenever we discussed taking breaks to manage stress, Arthur would always encourage it and say: 'when you're too stressed to take a break, *that's* when you should take a break.' Arthur, I want to thank you for the seemingly limitless support and guidance you have provided this past year. As his career suggests, he focused on the details *and* on the big picture. I feel so grateful for being able to say that I have had two daily supervisors: Arthur and Bas were always there to provide feedback or to pick my brain on something.

This project was not my first encounter with the topic of agrivoltaics. I first heard of this beautiful synergy between agriculture and solar PV through one of my favorite energy transition Youtube Channels: Undecided with Matt Ferrell. I enthusiastically presented the topic during the Master Programme's public speaking courses and brought it up as a possible topic for Linda Kamp's economics course. That is why I would like to thank my cohort for making my Master's fun and engaging, including Hilde, Patrick, Aditya, Mihir, Salem, Bouke and Gabriel, to name a few.

And while this project was unfolding, and despite my leave, the momentum at my startup, Biosphere Solar, never faded. I am very excited to get back to developing and commercializing the world's first circular and fair solar panel. I want to thank my co-founders Sï and Perine for giving space to my studies and having the deeply felt faith that I would return to you fresh and determined.

A final thanks goes out to all of my lovely family members and friends, who I was still able to see by weaving them into my ever-flexible and remote weekly work routine.

Enjoy reading, I hope it inspires you to imagine a holistic, synergistic, sustainable future.

Tim Kaasjager
Amsterdam, August 2024

Abstract

The agricultural sector holds the potential to integrate a resilient and renewable energy system due to high penetration of renewable energy sources. This study addresses the obstacles towards this transition. The first obstacle is the Dutch electricity grid. As of 2024, the greatest bottleneck in the Dutch energy transition is the lagging grid capacity. Instead of relying on grid power, matching local generation and demand of energy provides an elegant alternative. The second obstacle is that on-farm activity is powered mainly by diesel, since the majority of the demand is from tractor activities. To address these two challenges, this report investigates two primary aims: first, to provide an overview of the hourly and seasonal energy demand for dairy and open-field farms; second, to evaluate the feasibility of decarbonizing on-farm energy systems given the current grid capacity. The first aim was achieved by identifying the main energy-consuming activities in both dairy and open-field farming, revealing that dairy farming has consistent day profiles throughout the year, whereas open-field farming shows significant variability depending on crop needs and practices. The activities constituting most of the electricity demand on dairy farms have been found to be 1) milking, 2) milk cooling, 3) water pumping and 4) lighting. Feeding and grassland management (fertilizing and mowing) have been identified as the main diesel-consuming activities. For open-field farming, electricity is consumed largely for crop storage in the form of cooling or ventilation, or a combination. This contribution is small compared to the diesel consumption for field operations (mainly for tillage).

The second aim involved accurate modeling of various photovoltaic (PV) system architectures with TNO's BIGEYE software and linear programming (LP) optimisation using Open Energy Modeling Framework (OEMOF) to assess their impact on the feasibility of decarbonization. The findings suggest that while the choice of PV systems can dampen the mismatch peaks by several percentages, the type of farm and its specific practices play the most significant role. For open-field farms, minimal crop storage requirements and sowing/harvesting periods, such as broad beans and wheat, that align with PV yield profiles are more suitable for achieving self-sufficiency. Short-term forms of energy storage, shifting loads and clipping maximum PV power are measures that directly enhance self-sufficiency and decarbonization without additional grid reinforcement. The highest self-sufficiency rates reach to 82%, meaning that 18% of energy is supplied by the grid. From the results, decarbonization of farm loads using solar PV as main energy source demands short-term and long-term storage to neutralize mismatch. The report concludes with an outlook for further studies to enhance the reliability of energy demand data and suggests actionable and effective alternatives to grid reinforcement for the successful electrification and decarbonization of the agricultural sector. The most straightforward and pressing step in further research is broadening the scope to matching mismatch profiles with other prosuming systems, such as other farmers, towns and businesses, forming resilient energy communities.

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4.2 These two metrics serve as indicators of imbalance of the system and the degree to which they can balance one another. The potential electricity from hydrogen is equal to the surplus after short term storage balancing and represents useable electrical energy after well-to-wheel conversion of 0.28. This factor is used because it assumes that the most concentrated shortages are due to tractor operations, which are assumed to be supplied using hydrogen fuel cells (see Section 2.3.6). The two PV system extremes for hydrogen production are shown, to indicate the significance of choosing the PV system. 56

Nomenclature

AC Alternating Current

ACRRES Applied research for sustainable agriculture and energy

AF The figure is an adapted form, often translated.

API Application Programming Interface

ASABE American Society of Agricultural and Biological Engineers

BIGEYE A modeling tool used within the report

CBS Centraal Bureau voor de Statistiek (Central Bureau of Statistics)

CLO Compendium voor de Leefomgeving (Compendium for the Living Environment)

DC Direct Current

DHI Diffuse Horizontal Irradiance

EEMCS Electrical Engineering, Mathematics, and Computer Science

EU European Union

EV Electric Vehicle

FF Fill Factor

GHG Greenhouse Gas

GHI Global Horizontal Irradiance

GJ Gigajoule

GUI Graphical User Interface

ha Hectares

IV Current-Voltage Curve Solar Cell

KWIN Kwantitatieve Informatie Akkerbouw en Vollegrondsgroenteteelt (Report on Quantitative Information Arable and Vegetable Farming)

LP Linear Programming

MJ Megajoule

MW Megawatt

OEMOF Open Energy Modelling Framework

OFFarming Open-Field farming

OF Objective Function

PBL Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)

PERC Passive Emitter Rear Contact solar cells (largest market share cell technology)

PJ Petajoule

PPS	Referring to a Research Program from Wageningen University on Energy & Agriculture
PV	Photovoltaic
$PVMD$	Delft Research Group for Photovoltaic Materials and Devices
RT	Ray-tracing
RVO	Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency)
SAT	PV systems with Single-Axis Tracking
SDE	Dutch subsidy program for renewable energy projects
STC	Standard Test Conditions for solar PV modules.
TNO	Dutch Institution for Applied Natural Sciences
VF	View Factor

1 | Introduction

1.1. Research Motivation

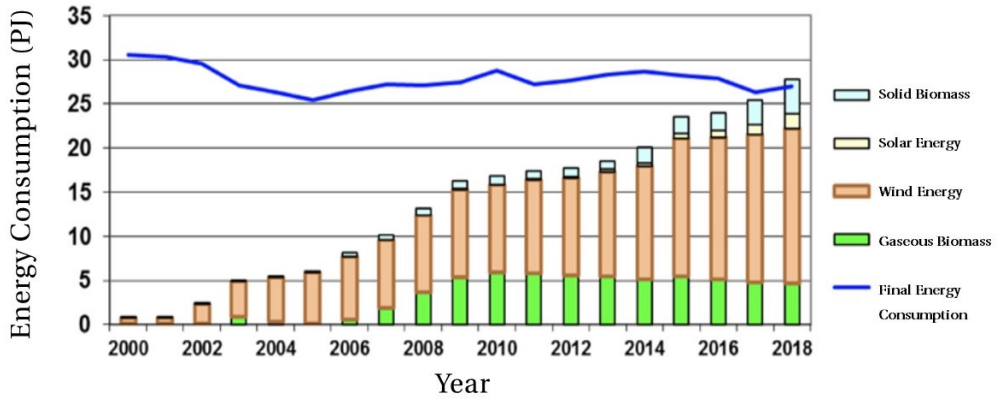


Figure 1.1: Final Energy Consumption and Renewable Energy Generation in the Dutch agricultural sector (excl. horticulture) over the past two decades [1][AF]. Since the annual consumption and generation are equal, a balanced system could be fully renewable. By 2022, the sector has become a net supplier, since consumption remains stable and renewable generation continues to increase [2].

The evolving dynamics of the global energy transition present both opportunities and challenges for the agricultural sector, necessitating a comprehensive examination of their interdependencies and potential synergies. The motivation for this study stems from a research interest in the nexus of solar energy and agriculture.

The Dutch agricultural sector presents a unique energy paradox. On one hand, the Netherlands has witnessed a rapid advancement in renewable energy generation within the agricultural sector, with on-farm production reaching levels comparable to the sector's total energy consumption, as shown in Figure 1.1. This Figure only provides data up to 2018, so other sources have been counselled for the more recent years: While annual energy *consumption* has remained stable between 2018 and 2022 [2] and report a dramatic increase in annual *renewable energy generation* of approximately 50 PJ, in line with the Dutch Regional Energy Strategy's goals for 2030 (83 PJ for renewable energy on agricultural land [3]). Besides a high installed capacity of wind turbines on farmland, 85% of agricultural enterprises have installed solar PV to some degree [1]. This progress is commendable, but a significant hurdle remains, which introduces the paradox. The Dutch agricultural sector itself remains heavily reliant on fossil fuels, hindering the potential for a truly sustainable food system [4]. It is one of the only sectors in The Netherlands that is not on schedule with achieving European emission targets for 2030 [3].

Even if the nascent and innovative efforts towards electrification of fossil-based agricultural loads [5] [6][7][8][9] would gain traction, grid congestion presents a major roadblock in The Netherlands. The existing grid infrastructure already struggles to handle the increasing demand and bi-directional flow of electricity as our industries and sectors decarbonize [10]. Farms are often located in the capillaries of this strained grid, meaning it will be especially difficult to transition towards electric loads and sources, *unless* these loads and sources can balance one another with minimal grid exchange. Currently, grid costs and energy taxes are being priced to stimulate self-sufficiency and reduce peak demand [11] [12]. In short, to maximize self-sufficiency will become a necessity for a carbon-neutral agricultural sector.

However, to study the potential of this parsimonious approach, a crucial piece of information is missing: comprehensive data on hourly and seasonal energy demand for different types of farms. For fossil-based energy systems, it suffices to know the aggregated yearly consumption of a sector. This is why most databases and reports only offer annual total energy consumption values [4] [13] [14] [15][16][17]. Since renewable energy systems have *intermittent* sources, hourly and seasonal data are crucial for accurately designing and implementing effective self-sufficiency strategies. Additionally, with electrification expected to significantly increase a farm's electricity needs [4][8][18], innovative approaches are required to meet this demand while minimizing exchange on the strained grid.

Agrivoltaics, the colocation of agriculture and solar photovoltaic (PV) systems, enabling multiple land use, is one such approach. By harnessing the power of the sun, agrivoltaics cannot only increase on-farm renewable energy generation but also potentially improve agricultural conditions and yield due to the creation of favorable microclimates under solar arrays and because evaporated moisture from plants condensates on the modules [19][20][21]. However, widespread adoption by farmers hinges on the economic and practical benefits it offers them. Despite the many practical benefits, such as better labor conditions, improved water and soil quality retention [22], and conditional crop yield increases[23], the business case is deemed infeasible for Dutch farmers, since agrivoltaic systems are less cost-competitive than ground-mounted solar farms, and the advantages are not yet recognized in the market and in policy [24].

1.2. RESEARCH OBJECTIVES

This study has two objectives. The first is to address the existing knowledge gap by taking the first rudimentary steps towards understanding the hourly and seasonal energy demand profiles of Dutch farms. With some empirical but close to no statistical data, the aim is to draft the first overview of the profiles for the main on-farm energy-consuming activities. The main energy-consuming activities are identified, and their hourly and seasonal profiles are illustrated. The sub-Research Questions for this first objective are:

1. **Which activities currently contribute significantly to electricity and diesel consumption on dairy and open-field farms?**
2. **How can their consumption profiles be modeled to quantify energy self-sufficiency and power exchange with the grid?**

The second aim is to evaluate the feasibility of decarbonizing on-farm energy systems, given the current grid infrastructure. This will be done by exploring the mismatch between energy demand and solar PV generation for various farm and PV system archetypes, given the current grid capacity for farmers. The sub-Research Questions to answer for achieving this aim are:

1. **If all loads on open-field and dairy farms become electric, how are 1) the energy self-sufficiency and 2) grid capacity needs affected?**
2. **How can *a) load shifting, b) power clipping and c) energy storage* on an electric farm 1) maximize self-sufficiency and 2) minimize grid capacity needs?**

The first reason this study focuses exclusively on the mismatch with solar PV yield profiles is that there is a remarkably low aggregated penetration of solar PV, relative to wind energy. Assessing the mismatch will help to understand what is holding this deployment back. The second is the aforementioned potential of agrivoltaics to improve both the performance of agricultural and PV systems. Through the simulation of different scenarios, this research will investigate the potential of agrivoltaics to enhance self-sufficiency and reduce the need for grid reinforcement within the Dutch agricultural sector. By evaluating the technical aspects of self-consumption through agrivoltaics, this study allows farmers, TSOs and policymakers to gain initial bearings when considering the integration of solar PV with agricultural energy demand.

1.3. SCOPE

Several boundary conditions have been set for the report. First, two segments within the agricultural sector are considered: the *open-field* and *dairy* farm segments. This is because agrivoltaics is most suitable to these two methods of farming. Despite its magnitude in the Dutch agricultural sector, horticulture will be left out. Second, the scope of the energy system will be kept 'behind the meter'. In other words, the system components on one farm's side of the grid connection, including the grid connection itself, will be considered. This also means only *on-farm* energy consumption is considered. Third, the on-farm energy source in the studied systems will be limited solely to solar PV and the available grid connection. Additionally, the available grid connection size is kept below the Dutch threshold for small-scale consumers. Fourth, although the implications for storage will be discussed, the focus of the paper is on matching of direct generation and demand. Fifth and lastly, the available sources, tools and network are those provided to students at the Delft University of Technology, interns at TNO and those publicly available online.

1.4. REPORT OUTLINE

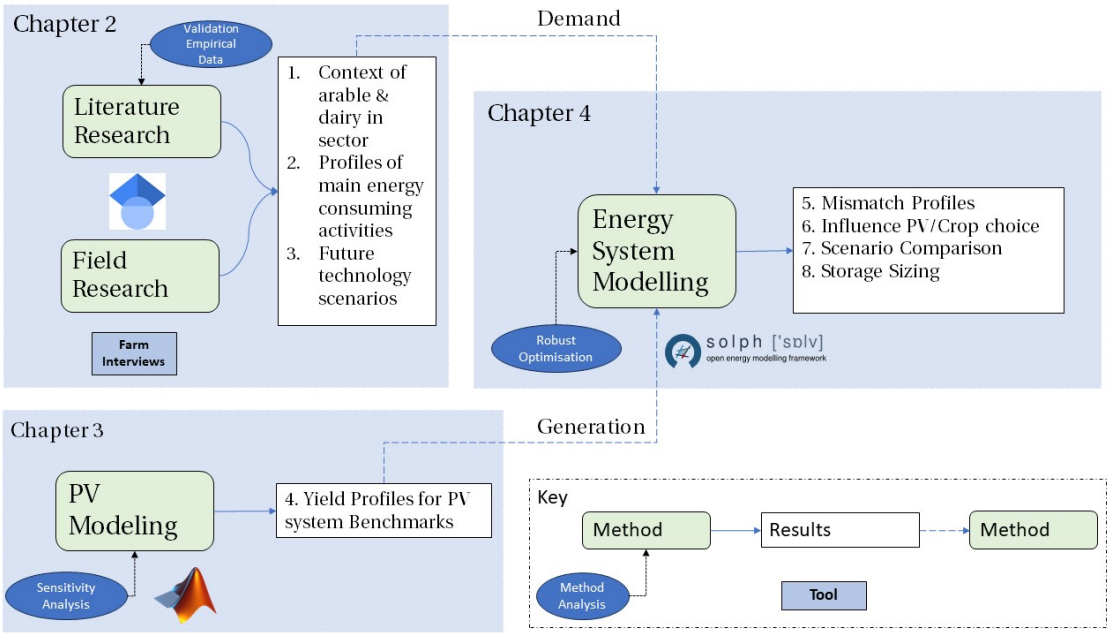


Figure 1.2: Overview of the methodological steps, including outputs. Method analyses take a look at the method itself to understand the reliability of the method. Dotted lines: 'informs'. The logos also describe the tools used, from left to right: Google Scholar (and other publication platforms); BIGEYE model built in MATLAB; OEMOF Solph, written in Python and powered by Pyomo, Python's linear programming solver.

In this introduction, it is described *why* this study was conducted. The next three Chapters are structured in the following way: the background is first described conceptually and then, the translation to programmed models is illustrated. To simplify reading, and because the methodologies vary strongly, each Chapter consists of an Introduction, a description of the Methodology and a discussion of the Results.

In the following Chapter, the research for and subsequent modeling of the energy demand is discussed. The method used is a combination of literature and field research, as indicated in Figure 1.2. An overview of the sector is first provided, after which the energy consuming activities on open-field and dairy farms are discussed in more detail. Lastly, these findings are translated to demand profiles for the energy system model.

Chapter 3 is dedicated to the modeling of solar PV systems. First, the concepts underlying contemporary PV yield modeling are discussed. This is followed by a discussion of the modeling software which is written in MATLAB. Lastly, the chosen PV system architectures, to be called benchmarks in this study, are discussed.

In Chapter 4, the demand and generation are integrated into an energy system tool. The tool uses farm-specific input to provide data insights on the supply-demand balance of energy system scenarios. Different scenarios, based on technological trends and possibilities, will be compared to study the effects on self-sufficiency and grid exchange.

After these Chapters, a discussion of the broader implications of this study is provided in Chapter 5. Lastly, results will be summarized and recommendations for future work are provided in Chapter 6.

2 | Energy Demand: Literature & Field Research

2.1. Introduction

In this first Chapter of the study, the main energy-consuming activities on open-field and dairy farms are discussed. This Chapter works towards the first objective of this study, which is to *address the existing knowledge gap by taking the first rudimentary steps towards understanding the hourly and seasonal energy demand profiles of Dutch farms*, as defined in Section 1.2. It aims to answer the following research questions, also defined in Section 1.2:

1. Which activities currently contribute significantly to electricity and diesel consumption on dairy and open-field farms?

2. How can their consumption profiles be modeled to allow quantification of energy self-sufficiency and power exchange with the grid?

The first question will be addressed in Sections 2.2 to 2.3. The second question will be addressed in Section 2.4 These research questions demand a descriptive approach. The subsequent Chapters, on the other hand, will be more predictive in nature. In contrast to these Chapters on predicting energy mismatch, *this* Chapter aims to understand the situation of energy systems as they currently are.

As announced in Section 1.4, Chapters 2, 3 and 4 are structured as fully comprehensive reports. Together, they form the parts needed to answer the research questions of this study.

First, the approach of the literature and field research and its limitations are discussed. Then, a review of the sector is provided, mapping the context of the two farm types that this study focuses on. Consequently, the total energy consumption, followed by the main energy-consuming *activities* will be discussed, ending with the energy consumption *patterns*. This is done first for open-field, then for dairy and thirdly, the loads that exist on both types of farms are bundled and discussed. Section 2.3.6, an outlook on future implications, offers a selection of future technological developments and bottlenecks that the literature deems of significant influence to the energy demand on farms. These results are then translated to building blocks for the energy demand in the energy system model in Section 2.4. The consumption patterns will be visualised and their specifications, such as stochastic aspects and power, will be summarized.

2.2. Methodology

As described in the introduction, the objective of this Chapter is to make the first rudimentary overview of on-farm energy consumption patterns. The refining of energy consumption data from annual totals to hourly profiles is a crucial task to conduct in parallel with the transition from fossil fuel systems to renewable energy systems. To address the gap in hourly and seasonal energy consumption data [16][25], academic literature research alone does not suffice. In this study, it was therefore complemented with interviews with and data from farmers and agricultural equipment manufacturers. 10 farmers from the provinces of Zeeland, Flevoland and Utrecht were interviewed regarding their energy consumption and barriers towards electrification. As a guide, a consistent questionnaire was used. The questionnaire can be found in Appendix (for the Appendix, refer to the digital edition). Casual conversation and a tour of the farm provided additional information. Once the main energy consuming activities on these farms were identified and cross-examined, datasheets containing power specifications of the machines were retrieved and interviews with their manufacturers were conducted to validate their typical use. The questionnaire in Appendix (for the Appendix, refer to the digital edition) also includes the questions posed to manufacturers. Consumption profiles were then constructed for each machine using Python, so it could be integrated into the model.

2.2.1. THEMATIC ANALYSIS

To analyse how confirming the interviews are of consumption patterns found in literature, the method of thematic analysis was used [26]. This method identifies common themes from a set of texts. The *deductive* variant of this method is a qualitative analysis of confirmations and refutations of preconceived themes. It therefore suits the approach of literature research followed by field research. To conduct a thematic analysis of a small set of interviews, the following steps are undertaken, taken from the original developers [26]:

1. Familiarization
    - This step involves structuring your data. It is done to make sure the data format of the interviews are consistent
2. Coding
    - This involves going through the answers and categorizing certain phrases into 'codes'. For example, a code could be *'Reluctant to generalize consumption patterns'*. If an interviewee answers to one of the questions saying *'this differs strongly for each task'* you add a tally to that code.
3. Generating themes
    - Codes need to be quite specific to retain nuance in the interviewees' statements. Once the interviews have been decoded however, more general trends are abstracted from the codes. This is done through themes: bundles of codes. In the case of this study, the themes are split in confirmations or disputations of certain assumptions.
4. Reviewing themes
    - In reviewing themes, a step back is taken to evaluate whether the themes relate to the coded phrases from the interviews.
5. Defining and naming themes
    - At this point, the researcher has been formulating themes in language that can be understood personally, but might need to be translated to more widely and publicly acknowledged terms.

This method was used for two reasons. The first is that the interviews served as a way to validate literature research, and is therefore vulnerable to confirmation bias. Thematic analysis helps avoid confirmation bias for several reasons, one of them being the tallying of disputations of the findings from literature in Step 3 [27]. The second reason is the small number of interviews. Thematic analysis is grounded in a qualitative analysis of interviews, rather than quantitative, making it applicable to small sample sizes.

Note that this analysis was conducted to indicate the extent to which the interviews confirmed or dispute the assumptions about energy consumption. It has therefore not directly influenced the models developed in Section 2.4, but only indicates the confidence, or lack thereof, that the interviews showed towards the assumptions. This confidence is represented by a percentage of confirmation and disputation, alongside the sample size and can be found in Tables 2.4 and 2.5 for dairy and universal loads, resp., and in Section 2.4.1 for open-field loads.

2.2.2. DATA LIMITATIONS AND BIAS RISK

It must be repeated that there are fundamental limitations to how close the collected data is to reality. First, because of the limited sample size of farmers and manufacturers, the conclusions were drawn from anecdotal data, with little statistical weight (no more than 15 interviews). Secondly, data of energy consumption from farmer testimonials are not empirical measurements, so misconceptions of

the farmer's own energy consumption cannot be ruled out. Both limitations are quantified with the thematic analysis.

Besides limitations in assessing a farm's energy consumption mentioned above, the diversity in practices and machine models also limits the validity of data. Specifically, it is hard to generalise the consumption of farms, even when their characteristics are identical. For example, two farmers could be almost identical companies: both growing 60 hectares of potatoes in Flevoland. But if they use subtly different types of ploughing equipment, they can have significantly different diesel consumption when preparing their seedbeds.

In Section 2.4, where the chosen load models for the machinery are described, emphasis is placed on the underlying assumptions and simplifications made when setting the parameters.

2.3. RESULTS

In this Section, the findings from the literature and field research are provided. First, some general numbers concerning the sector are provided. This places the two studied farm types in the context of the sector as a whole. Each farm type is then studied in further detail, starting with its total energy consumption, followed by the main energy consuming activities and the daily and seasonal patterns of these activities. Lastly, an outlook of technological trends and possible bottlenecks is provided.

2.3.1. SECTOR REVIEW

This section provides a review of the agricultural sector's energy system. It serves as context for the two segments relevant to this study: open-field and dairy. Although *daily* and *seasonal* agricultural demand patterns are not well studied, there is extensive data on *yearly* consumption of the entire sector and of different farm types (although the data is ambiguous, as will be discussed). Horticulture is not included in this study, but it is illustrative of the scope of our study to indicate each segment's contribution. The sector-wide energy consumption, GHG emissions and renewable energy generation is shown in Figure 2.1. It is useful to realise that the two chosen segments constitute roughly 20% of total energy consumption of the sector.

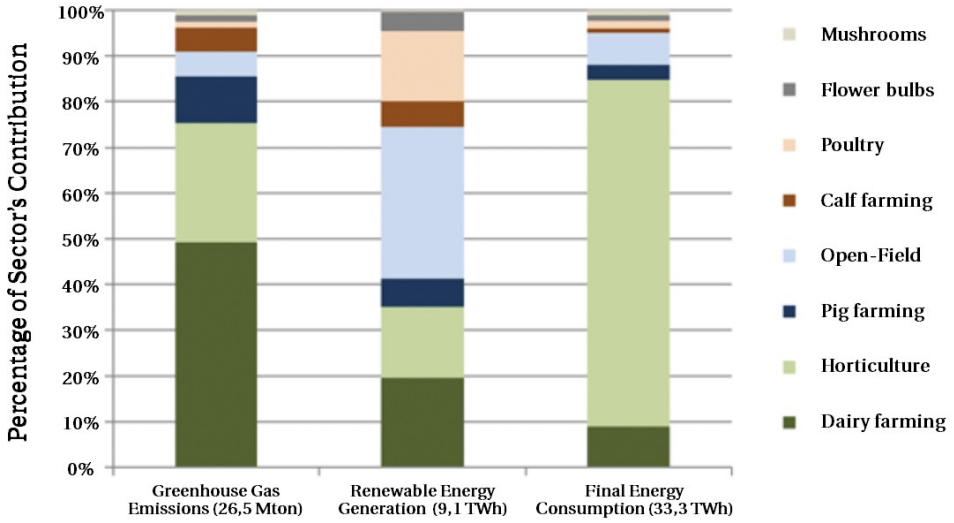


Figure 2.1: Indications of final energy consumption in 2020, generation of renewable energy and GHG emissions for the different Dutch agricultural segments[1]. The totals are also provided. If horticulture were to be left out, as in Figure 1.1, the consumption and generation of renewable energy would be roughly equal.

Open-Field and Dairy are two interesting segments to compare, since their contribution to final energy consumption is similar, but their contributions to renewable energy generation and GHG emissions are inverse. Due to the large land area needed for open-field farming, wind power projects are often developed on or in between farming lots. No plausible explanation was found for why this is less the case for dairy farming, despite the fact that 25% of Dutch land is used for grazing livestock (around 10% for open-field farming) [14].

If horticulture contributes to the majority of energy consumption, one would prioritize efforts on balancing the horticulture's future energy system. Horticulture, in this figure, has low emissions for the amount of energy consumed. However, to understand how efficiently horticulture uses its energy for cultivating food crops, the energy consumption must be compared to its agricultural output.

Horticulture is an energetic powerhouse, with an energy footprint per kilogram of produce that is orders of magnitude higher than open-field farming [28]. Therefore, from energy management perspective, horticulture is an irresponsible method for producing food and is left out of the scope of this study. In Appendix, a comparison between different carbon footprints for lettuce is provided. It is crucial to understand that these values are indications to be studied with scrutiny. The reason is that the values vary between (renowned) sources. Wageningen University, for example, indicates that horticulture consumed 29 TWh, dairy farms consumed 2.1 TWh of energy and open field farms consumed 1,3 TWh of energy in 2020 [29]. The final energy consumption in Figure 2.1 is lower than the 46.5 TWh that CBS reports [13]. This comes to show that the data can vary strongly between different sources, seemingly due to varying scopes of the energy analyses. For example, it is not always clear whether indirect energy consumption is considered and whether net or gross electricity consumption is considered.

Narrowing down to the dairy and open-field farming segments, some general data are now provided. Being two of the most exhaustive sources, on-farm energy consumption data from Wageningen University's aforementioned database Agrimatie have been combined with statistics the Dutch Central Bureau for Statistics (CBS) and are shown in Table 2.1. Land use and number of farms are derived directly from CBS and corresponding energy densities per farm and hectare have been calculated using energy consumption data.

Table 2.1: Yearly energy consumption in terms of land use and per farm, for four farm types in the Netherlands. Sources from CBS/CLO[18][14] and Agrimatie [29], with data from 2023.The data per farm and hectare is found by dividing the values above. The values are therefore averages.

	Open Field	**Dairy**	**Granivore**	**Mixed**
Number of Farms	12,711	14,700	3,799	2,993
Energy Consumption (GWh)	1,311	2,111	1,528	556
Land Use (thousand ha)	548	882	84	160
Average Size (ha)	43	60	22	53
Energy Consumption per hectare (MWh/ha)	2.39	2.39	13.2	2.6
Energy Consumption per farm (MWh)	103	144	292	139

The energy mix from Agrimatie differs significantly from a study done by CBS and Compendium voor de Leefomgeving (CLO)[30] referenced in [18]. It is therefore important to stress that energy demand figures should not be taken as unassailable.

These average farm sizes indicate that many of these enterprises are not utility-scale energy consumers. If they were to adopt agrivoltaics on a large part of their land, they would therefore become a producer rather than a balanced prosumer, since the energy generation of agrivoltaics can easily reach 1,000 MWh/ha. To reach their own energy consumption, a farm would not need more than a few thousand square meters (1 tenth of a hectare). Of course, due to the intermittent nature of solar PV, this does not mean all the energy can be used by the farm (elaborated on in Section 4.3). The average size for farms will also become more relevant for the sizing of the energy system models in Chapter 3.

The energy intensity per hectare for dairy and open-field farming is the same, making their demand profiles interesting to compare. The demand for the granivore business is higher, illustrating the difference in intensification. In the past decades, farming in general has intensified in The Netherlands: the number of farms has roughly halved since 2000 [14], but the output has increased [31].

2.3.2. ENERGY DEMAND OPEN-FIELD FARM

Now that the broad figures of the sector have been mapped, this section provides a more in-depth discussion for the case of open-field farming. The term open-field farms refers to both arable and

vegetable farming. Arable farming refers to the practice of growing crops for staple foods and fiber, such as corn, wheat and cotton. Vegetable farming in this report refers to the cultivation of vegetables in open fields. Since this distinction is often made in literature, two values or graphs will often be shown.

Furthermore, the literature research conducted was cross-validated by visiting five open field farms, an agricultural contractor and two equipment manufacturers. The extent to which the data in this Section was affirmed and disputed by these interviews can be found in Appendix.

Again, only on-farm energy consumption is considered. This is a consideration to keep emphasizing when handling numbers about energy consumption, because indirect, or off-farm, energy consumption can amount to 70% of total agricultural energy demand[32]. This same study shows that seed and fertilizer production have a major contribution to indirect energy consumption.

TOTAL ANNUAL ENERGY DEMAND

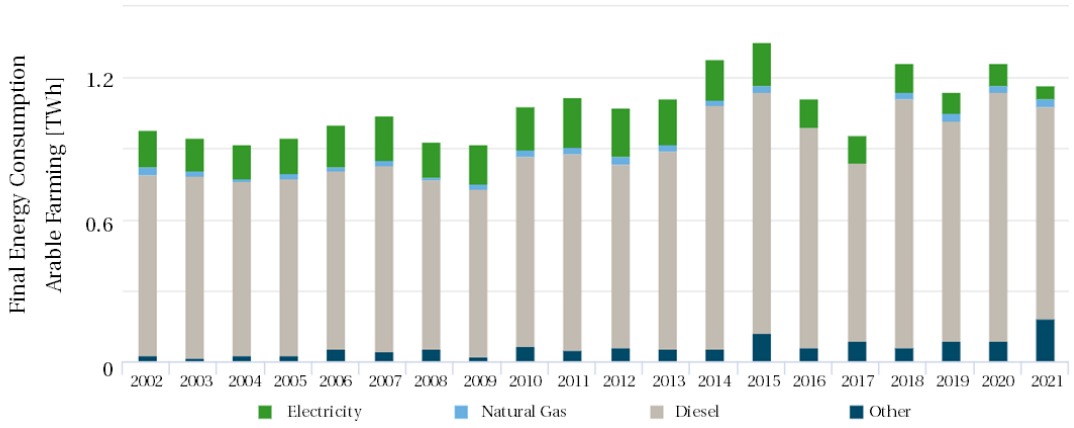


Figure 2.2: Total net energy consumption of Dutch arable farming sector[29].

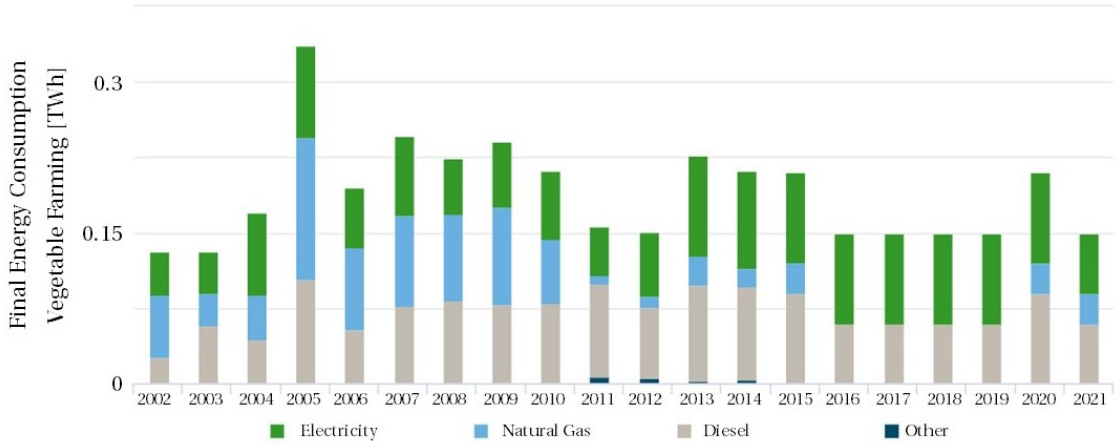


Figure 2.3: Total net energy consumption of Dutch vegetable farming sector[29].

The *total annual* energy mix of open-field farming in the Netherlands will first be discussed. Total sector numbers are provided, as opposed to energy consumption per kg of produce, as it is more instructive to the impact on grid congestion. In Figure 2.2, it is shown how the on-farm energy consumption of the arable farming sector has developed since 2002. It can be observed that net

electricity consumption has decreased. Increased PV deployment would be a plausible explanation for this decrease. Since agriculture is not a distinguished sector in solar PV deployment reports, it was not possible to find data on solar PV deployment specifically on farm roofs. To emphasize again how data can vary, the energy consumption in Figures 2.3 and 2.4b amounts to a total of 1.4 TWh, which is noteably lower than the data illustrated previously in Figure 2.1: 2.0 TWh.

It can also be observed that the dominant energy source of arable farming, and to a lesser degree for vegetable farming, which is shown in Figure 2.3, is diesel. For vegetable farming, electricity is a more significant source. This can be explained by the crop cooling and ventilation needs for vegetables, as will be discussed in the following section. Note that vegetable farming has an energy consumption roughly one order of magnitude smaller than arable farming. This can be explained the Dutch focus on horticulture for vegetables. Arable crops being unsuitable for horticulture, this segment has retained its share.

MAIN ENERGY CONSUMING ACTIVITIES

In this section, energy consuming activities *specific to* open-field farming are discussed. The main energy consuming activities for open-field farming, based on indications from literature and re-affirming responses during farm interviews are:

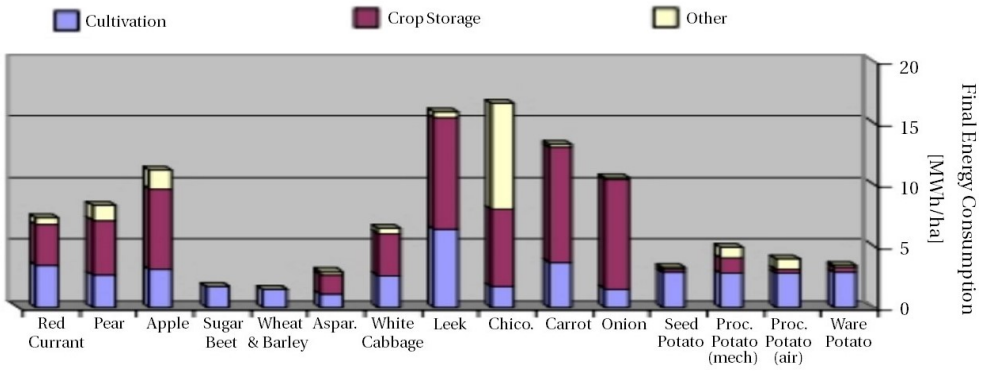
- Field operations
- Crop storage
- Storage line

Field operations refer to the use of tractors to prepare and maintain desirable soil conditions for growing. It is clear from Figures 2.2 and 2.3 that the main energy source of open-field farming is diesel, and this is largely attributed to field operations. Crop storage refers to the drying and/or cooling of crops before they are dispatched. The storage line is used to transfer produce from the harvesting equipment to the desired storage setting. Farmer interviews pointed out that the storage line contributes to electricity consumption, but that crop storage is the dominant factor, as will be discussed further below.

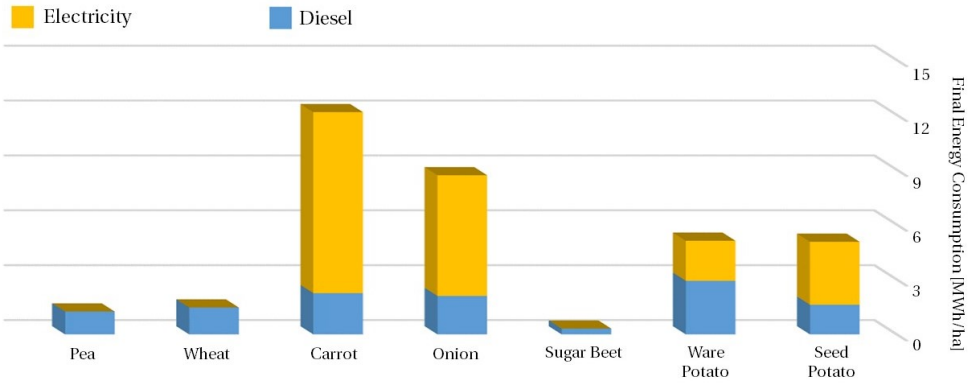
For these three activities, the variety in power demand is too large and dependent on too many factors to make a general division of their contributions to energy contribution. Since the energy demand and mix of open-field farms depends most significantly on the type of crop [32][33], the distinctions are provided in Figure 2.4a. It shows the energy demand per hectare for different crops, split between different steps in the production process. According to the source, 'Other' is the on-farm processing of the crop, such as the sorting and scrubbing of potatoes.

One would hypothesize, that the 'Cultivation' step and two steps of 'drying/storing' and 'other' are also a sound distinction between the two main energy inputs: diesel and electricity, resp. In Figure 2.4b, the energy consumption per kg of produce for different arable crops is provided from another study. By comparing Figures 2.4a and 2.4b, there is support for this hypothesis, since the ratios of electricity over diesel are comparable to ratios of 'drying/storage'+'other' over 'in teelt'.
The factors influencing power demand for different activities will now be characterized. For field operations, work is achieved using tractors at a constant power, in which the throttle is only reduced when turning at the end of a row[36]. The power measurement conventionally used for tractors is the drawbar power $P_{drawbar}$ in Watt, which is the result of incorporating losses of the transmission system of the tractor from the gross engine power. The efficiency of the useable power $P_{drawbar}$ with respect to engine power varies strongly depending on the quality of the engine and the soil type, ranging between 48-67% [37]. Mechanical power can be defined as the product of a force and the velocity. Along this definition, the drawbar power required for a certain task can be estimated as [37]

$$P_{drawbar} = R_{soil} \cdot v_{work}, \tag{2.1}$$



(a) Energy consumption for common Dutch crops in 2010, split into three process steps [34](AF).



(b) Energy consumption for common Dutch crops in 2014, split into energy sources, based on GJ/tonne values from [33] and expected crop yield in tonnes from [35].

Figure 2.4: Energy consumption of Dutch arable farming for different crops in GJ/ha, split (a) into different steps of growing and processing and (b) into different energy sources.

where v_{work} is the working speed of the tractor in m/s and R_{soil} is the soil resistance in N. R_{soil} is dependent on the cross-sectional area of the soil being tilled. It can be calculated as

$$R_{soil} = W_{impl} \cdot d_{work} \cdot R_{task}, \tag{2.2}$$

where W_{impl} is the width of the implements attached to the back of the tractor in meters, usually equal to the row width of the field. d_{work} is the depth up to which the implement tills the soil in centimeters and R_{task} is the task-specific resistance in $\frac{N}{m \cdot cm}$. Different values for R_{task} are presented in the Appendix. R_{task} in literature can vary between $242 - 1281 \frac{N}{m \cdot cm}$ for different tasks, and farmer testimonials are not congruent when presented with a list of tasks ordered by draft force. Furthermore, farmers indicate that soil conditions are one of the most influential factors on the power demand. The values in Table **??** are considered for clayey soil. These three points caution against the generalisation of field operations.

For the characterisation of crop storage power demand, the two manufacturers of storage systems in The Netherlands that constitute the majority of the market share were counselled. Crop storage consists of cooling, ventilation, or both. The manufacturers stated that there are four crop categories between which to differentiate storage requirements. The cooling demands for these types of crops are provided in Table 2.2. The rule of thumb used by the manufacturers for ventilation capacity is to account for $20 \frac{W}{ton}$ for all crops. Where potatoes and onions have similarly structured cooling and ventilation patterns but parameters are sized differently, the latter two categories are fundamentally different: Root vegetables are solely cooled and grains are solely dried.

	Onions	Potatoes	Root Vegetables	Grain
Cooling Demand [W/ton]	50	35	65	0
Crop yield [ton/ha]	40	33	40	5
Crop Storage Installed Power [kW/ha]	2.8	1.8	2.6	0.1

Table 2.2: Values for calculating the required installed power for storing crop types, based on interviews with crop storage manufacturers. The installed power value accounts for the 20 W/ton of ventilation demand required for all crops but root vegetables. For grains and root vegetables, the average crop yield per hectare for the most commonly tilled crops was taken.

To gauge whether the contribution of the storage line is significant, a farm with an average size of 39 hectares and the crop with the most energy-intensive storage line: potatoes, will be considered. Such a farm will employ up to two conveyor belts and a hall loader, which transport the potatoes into the barn, and a hopper, which scrubs and sorts the potatoes. This amounts to roughly 23 kW, used during harvesting. Assuming 5 days of harvesting from 08:00-20:00, that amounts to 1.38 MWh. The number of conveyor belts depends on the size of the harvest. In Table 2.1, we have seen that farm energy consumption lies in the range of hundred(s) of MWh. Storage line energy consumption is thus only a small contribution.

HOURLY DEMAND PROFILES

We will now look not only at installed maximum power, but during which hours of the day and week of the year this energy is demanded. To verify the diverging data and obtain more insight into daily and seasonal energy consumption patterns, the literature was cross-examined with farmer interviews. These findings will be used in Section 2.4 to simulate power demand datasets for the different load types.

In Figure 2.5, the yearly energy demand of a case study of a monitored arable farm is shown. These values were calculated in [18] using the farm parameters and several sources, not based on actual measurements on energy consumption. The farm cultivates a mix of the most common crops in The Netherlands: potatoes, onions, sugar beet and grains. The peaks in diesel consumption can be attributed to the tillage before and during sowing and harvesting.

The electricity consumption can be attributed largely to the crop storage. After harvest, the suitable combination of cooling and ventilation for that crop is operated 24 hours a day, until a stable condition in terms of temperature, humidity or both is achieved. After this phase, cooling hours are brought down gradually towards 6 hours per day and ventilation at 2 hours per day. This is influenced by ambient temperatures and the storage content. What is also noteable from Figure 2.5 is the baseload electricity demand is around 1000 MJ per week throughout the year. It is not mentioned what the source is, but it coincides with an average farmstead's consumption.

Electricity consumption is clearly out of phase with solar generation peaks for crops that are harvested in the fall. This is unfavorable for solar, furthermore because (a) most crops tilled in the Netherlands are harvested in fall [35], and (b) because crops tilled in the fall have the highest storage energy demand (onions, potatoes and root vegetables). However, crops that are harvested in summer, such as summer barley, summer wheat and cauliflower, could be well matched with solar PV generation.

Lastly, flexibility in crop storage demand could be achieved by exploiting the hysteresis of the cooling system. When the sun shines, the temperature would be reduced further than normal and when it does not, the temperature could be allowed to rise further. However, it is unclear how much loss of produce the farmers will suffer from increasing the hysteresis threshold.

Based on interviews with farmers and contractors, field operations are usually executed over the course of several days or weeks, fitting in as many operational hours in a day as practically possible. If weather

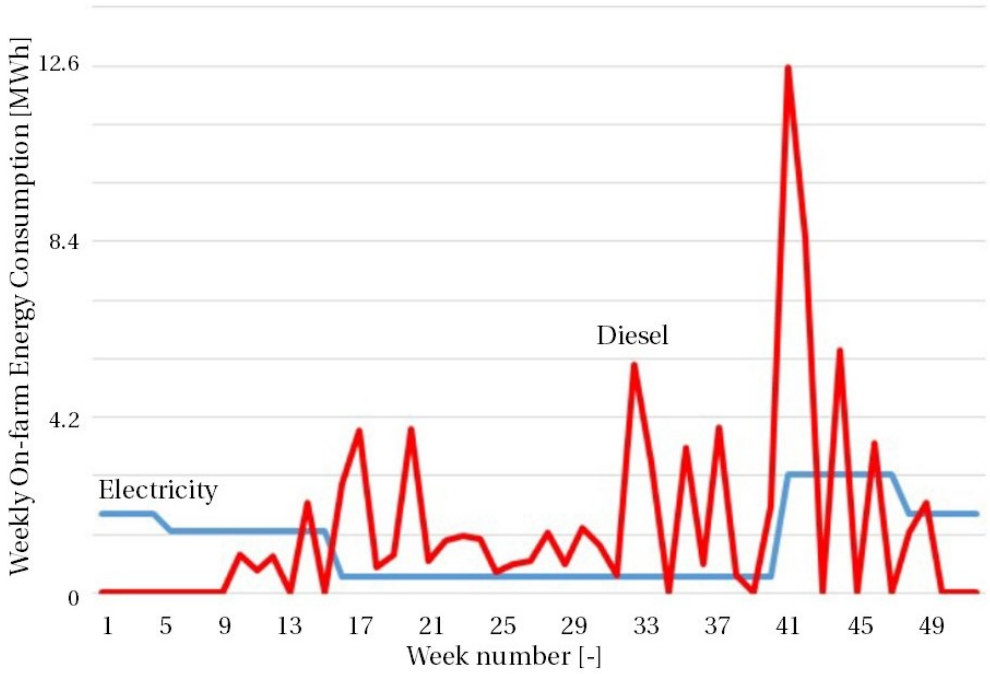


Figure 2.5: Weekly final diesel and electricity consumption in MJ for a model case study from literature [18]. The highest peak corresponds to harvesting activity, aligning with the increase in electricity consumption from switching on crop storage.

allows, starting at 7 AM and finishing at 10 PM is commonplace and desirable for farmers. Referring to the drawbar forces in Table **??**, a conventional 3 meters of implement width and 20 centimeters of tilling depth, power demands can range from 14 - 77 kW. This amounts to 210 - 1,200 kWh of energy during one day of operation, which agrees with a study done on battery sizing for electric planters [36]. In terms of seasonal timing of energy demand, this is very strongly crop-dependent. As mentioned in the discussion on crop storage demand, the most commonly grown crops in the Netherlands are harvested in the fall [35], although there are exceptions such as summer wheat, summer barley and cauliflower. Whether field operations will match with solar PV generation also depends on the powertrain, such as the considerations of using either batteries or overhead cables, which will be discussed in Section 2.3.6.

2.3.3. ENERGY DEMAND DAIRY FARMS

In this section, the findings from the complementary literature and field research will be discussed.

TOTAL ANNUAL ENERGY DEMAND

While studies often stress the global warming potential of dairy farms[38][39], on-farm energy demand per hectare is in similar orders of magnitude with other farm types (see Table 2.1). The discrepancy is due to the emissions of grazing livestock themselves and fertilizer use [33]. The annual energy consumption on dairy farms is shown in Figure 2.6. Again, the total from this source in 2020, 2.2 TWh, is lower than the total from the data in Figure 2.1: 3.0 TWh. The motorfuel consumption has increased by approximately 20% since 2002 and electricity consumption has increased by 45%. However, the database suggests that net consumption is shown. Therefore, gross electricity consumption is likely higher than in Figure 2.6 due to for example solar PV deployment, but there is little evidence to support the scale of the difference.

2.3.4. MAIN ENERGY CONSUMING ACTIVITIES

For grasping the potential for local agricultural energy consumption, it will be paramount to distinguish the main on-farm energy consumers. First, the main electricity consumers are considered. From various papers[40][41][42][43], the ranges of electricity consumption for the following five

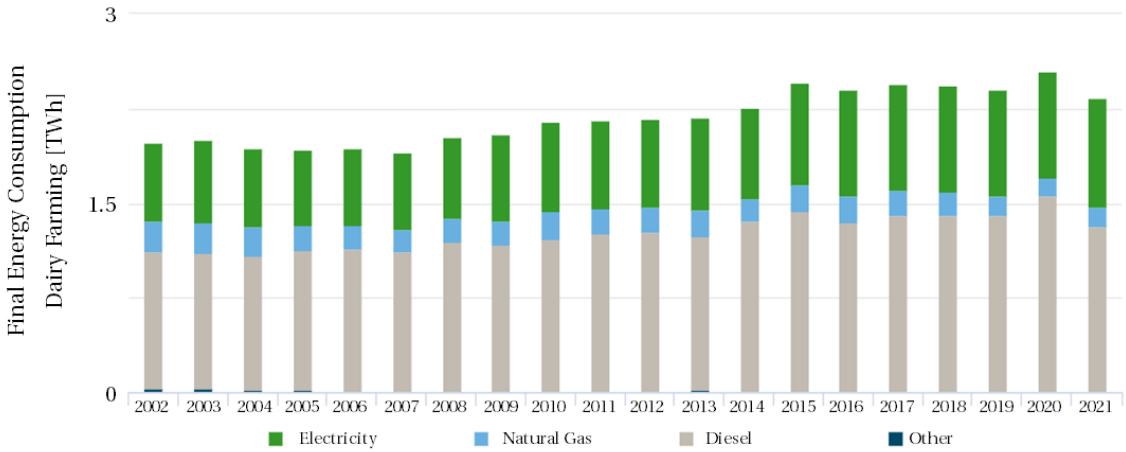


Figure 2.6: Total net energy consumption of Dutch dairy sector[29]

activities or machines have been determined:

- Milking machine 20-40%
- Milk cooling 19-32%
- Water heating 10-15%
- Lighting 4-16%
- Water pumping 6-12%

The electricity consuming activities are represented in relative percentages instead of absolute values per kg of farm output, due to the divergence in energy consumption per kg of output on dairy farms (in some studies, the lowest calculated energy consumption per kg of milk is threefold smaller than highest calculated energy consumption[44]).

This variation is particularly strong for the milking system. Although these large differences are partly because studies often refer to traditional and automated milking systems interchangeably [40] (elaborated on in Section 2.3.6), significant differences are reported between traditional milking systems (between 8.19 and 23.01) [43]. If we take the mean of the studies from this literature review, the result is 150 kWh per cow, assuming 9000 L of milk per year [45]. Assuming the average cow herd of 110 for Dutch farms [4], a yearly energy demand of 16.3 MWh is found.

In the Netherlands, most energy consumed during the milk cooling is from cooling the milk from the cow's body temperature to storage temperature. In a study done by TNO in 2014, milk cooling is estimated to consume between 8.2 and 8.7 kWh per 1000 L of cow milk. With the same assumption as for the milking system, this results in an energy demand of 8.1-8.6 MWh. Variety in cooling energy efficiency depends on the type of machinery.

Furthermore, it is commonplace in The Netherlands to exchange heat with the heating of water for cleaning the milking system. These exchangers can usually bring water temperatures to approximately 55 degrees Celsius, but system cleaning is conducted at 80 degrees Celsius. The water therefore only needs to be heated from 55 degrees to 80 degrees.

Lighting electricity consumption varies in the different studies and is difficult to pinpoint in the energy consumption of farmers, since it is a fairly low but consistent form of consumption [46][40]. Farmers therefore had difficulty pointing it out in their energy consumption reports. In some studies, it is even explicitly omitted from the overviews of on-farm energy consumption[43]. Considering the low contribution and high uncertainty, it will be sensible to omit it from the energy system model.

Groundwater is used in 87% of farms as source of drinking water for cattle[47]. To achieve this, the aforementioned heating system and exchanger and the initial pumping machinery need to be operated. To size the demand, let us consider that a dairy cow consumes anywhere between 70 and 240 L of water per day [48], and consider the Dutch average of 110 cows on a farm [4]. The machinery available at one of the farms will be considered. Like 87% of Dutch farmers, groundwater is the water source [49]. The groundwater pump has a power demand of 3.38kW and can pump 7 cubic metres each hour, resulting in 0.48 kWh / 1000 L. The pumps for transporting the water to the troughs demand 1.5 kW and can pump 9.5 cubic metres each, resulting in 0.16 kWh / 1000 L. For this farm, this results in 1.8-6.2 MWh yearly, depending on climate conditions and on the size of the cow.

For diesel consumption, the main on-farm energy consuming activities are:

- Manure moving
- Feed mixing and pushing
- Grassland management
- Miscellaneous barn moving tasks

For diesel consumption, no contribution percentage have been added as with electricity consumption. Acquired sources [32][18] state qualitatively which operations constitute the diesel demand, but no studies monitored operations separately. This could be explained by the indirect nature of fossil fuel consumption: diesel is refilled regularly in response to an empty tank. Tank content is rarely measured both before and after an activity. A second argument for the lack of quantitative study could be the complex nature and extensive number of factors influencing diesel consumption on dairy farms, making diesel consumption difficult to scale to a metric such as the number of cows or hectares on the farm[50].

HOURLY DEMAND PROFILES

In this section, the seasonal and daily demand patterns will be discussed, followed by initial observations of its overlap with solar PV power generation and initial bearings on possible flexibility of the load. In the literature, subannual (daily and weekly) energy demand data could only be sourced from case studies, where one or a handful of farms were monitored throughout the year. Therefore, the interviews with farmers, machine manufacturers and distributors provide significant support for the following findings. In Section 2.4, these findings will be simplified to simulate power demand datasets for the different load types.

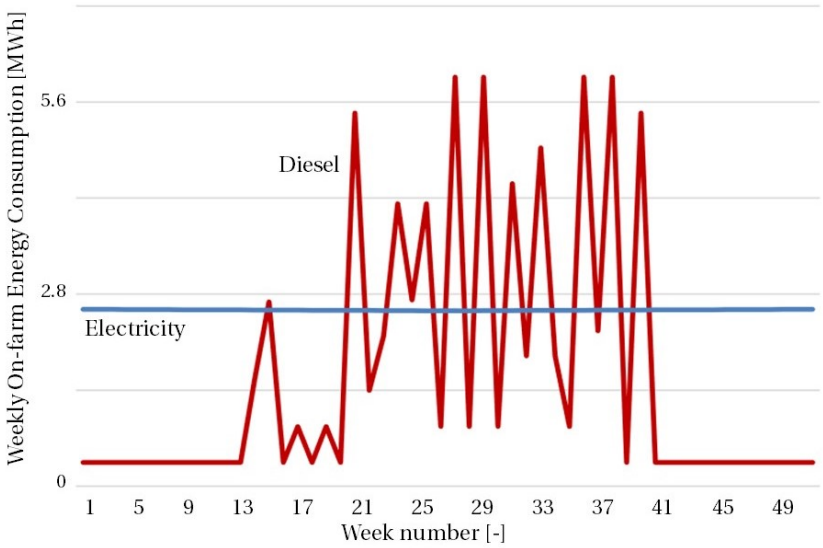


Figure 2.7: Final electricity and diesel consumption on a model dairy farm found in literature [18].

As with open-field farms, the case studies on dairy farms conducted by Wageningen University as part of the PPS Energie & Landbouw project are particularly informative for the seasonal, and occasionally for the daily, demand patterns [18] [51]. In Figure 2.7, values for a monitored dairy farm are shown. In the study, the electricity consumption has been assumed to be constant, after concluding negligible fluctuations throughout the year.

In contrast to electricity consumption, diesel consumption appears to have strong seasonal fluctuations. The mixing and feeding of cattle consumes approximately 20% of annual diesel and has a consistent daily routine. The farms that were visited indicated that feeding takes an hour and is done in the morning around 8. The feed is then pushed towards the cattle several times during the day.
The remaining 80% of diesel consumption in this case study is mainly attributed to field operations.

Inquiries into the daily patterns for dairy energy consumption have been conducted during the interviews. All farms used traditional milking systems. Milking is normally the first and the last thing a farmer does during the day. This means for many farms that milking is done from 6-8 AM and from 17-19:00, both followed by a 30 minute cleaning process. Traditional milking parlors consume anywhere between 4.0 and 17.0 Wh/kg of milk [40]. The average energy consumption per cow per year is therefore approximately 96 kWh, taking 9000 L of milk production per cow per year [45]. During the cleaning process, part of the water heating takes place. Being a fairly energy-intensive process, it often exceeds the solar PV generation of an adequately sized barn rooftop solar PV installation. The routinely nature of the operation suggests low temporal flexibility.

Based on conversations with the manufacturer with the largest portion of the Dutch market for milk cooling systems, the operations behind milk cooling and consequential energy demand was characterized. Milk at 35-37 degrees Celsius is brought into the cooling tank straight after milking. This means that all stored milk is cooled back to 4 degrees Celsius after each milking process. In The Netherlands, milk is always picked up every three days. The difference in temperature between the milk and the desired temperature therefore decreases over the three days. In the aforementioned study done by TNO in 2014, it has been shown that cooling milk, from 35 to 4 degrees Celsius, after the first milking process since emptying the tank, consumes between 7.516 kWh/1000L and 8.295 kWh/1000L of cow milk, and cooling an almost filled tank just before pick-up from 9.1 to 4 degrees Celsius consumes 8.809 kWh/1000L and 9.074 kWh/1000L of cow milk. This is non-trivial, considering that

simplified calculation of the energy needed to cool a substance is equal to

$$Q = m \cdot C_p \cdot \Delta T, \tag{2.3}$$

where the thermal energy Q is in Joules, and ΔT can be in Celsius or Kelvin. The mass m and temperature difference before and after cooling, ΔT, have increased and decreased by a factor of 6, respectively. The higher energy requirement for smaller ΔT can be attributed to the rediced efficiency in cooling systems at lower temperatures and with smaller for lower ΔT, the technical reasoning for it being beyond the scope of this report.

In the same TNO study, the time needed to cool is shown to be approximately 1.5 hours. Furthermore, the cooling tank is equipped with a condensation plate and glasswool, in such a way that for temperatures up to 32 degrees Celsius, the hysteresis threshold of the cooling system is only reached in 12 hours: within the time range of the following milking process. There is therefore no power demand other than after the two milking processes.

According to farmers, two steps take place in water pumping: pumping up groundwater and above-ground pumping to the drinking troughs. The groundwater pumps operate 20 hours a day, usually the off-hours are at night. Above-ground pumping operates approximately 16 hours a day. Both have roughly equal power input, but this ratio can vary strongly depending on the way the farm is arranged.

VALIDATION OF ELECTRIC LOAD PROFILE

When the assessments above are bundled, they can be reconciled with a profile found in literature [52], which is shown in Figure 2.8. These are the mean values of 22 dairy farms in Ireland, with two clear peaks each day for milking. The mornings have a second peak that can be attributed to the cooling of the milk, but the evenings do not. There is also a baseload of electricity that can be explained by lighting and water pumping.

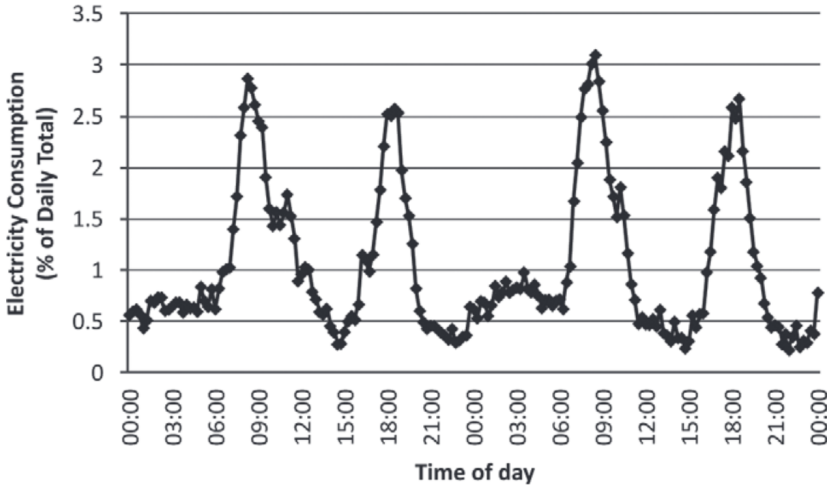


Figure 2.8: Hourly electricity consumption of 22 dairy farms. The unit on the y-axis indicates each data points' contribution to the daily energy consumption, in percentages [52].

2.3.5. UNIVERSAL LOADS

Based mainly on farm visits, there are four types of loads that are commonplace in both farm types:

- Car
- Light barn mover
- Farmstead
- Irrigation

For cars, the adoption of electric driving seems to have a low threshold due to the large photovoltaic installations on most farms. The number of driven kilometers per car can range between average yearly kilometers of 15,000 km [53] to the 60,000 km that some farmers claimed to be registering. Within that range, and considering a Mercedes-Benz EQV minivan's battery-to-kilometer ratio with a higher boundary of 35.5 kWh / 100 km, yearly electricity consumption comes down to 5.3-21.3 MWh. This is not insignificant, considering the values in Table 2.1.

Light barn movers refer to any machine meant for miscellaneous moving tasks in and around the barn, including shovels, telehandlers and forklifts. The movers come in a range of sizes from 18 kW up to 55 kW. Based on farmer testimonials, these movers are used for about 2.5 hours a day. A medium-sized shovel is therefore estimated to consume 30 MWh.

A farmstead can be considered an average household, depending on the farmer's family constituents. In The Netherlands, a family household consumes approximately 3,000 kWh of electricity and 1,200 normal cubic metres of natural gas. The energy from gas can be translated to 11,700 kWh, reaching a total of 14.7 MWh.

Irrigation is not a standard practice in Dutch agriculture, only when there is little rainfall. Most Dutch farmers use an irrigation reel, and since there is a favorable business case for electric, this is the most common energy source [54]. In [55] the conversion factors for sizing energy consumption are provided: a common water demand for crops translates to 3 hours per hectare are needed using a 30 kW reel. For an average farm size of 39 ha of arable land (Table 2.1), this amounts to 3.5 MWh per round of irrigation. Assuming, for open-field, that this is done at least three times a year: after sowing green manure, after sowing crops and during a hot period in the year, this amounts to 10.5 MWh yearly.

HOURLY DEMAND PROFILES

According to farmers, their cars were either used for trips shorter than an hour or for day trips, in which the car will leave in the morning and arrive in the evening. In the testimonials, the barn movers are normally used for an average of 30 minutes, for a total of around 2.5 hours each day. Household energy demand patterns are thoroughly studied and made public by the Dutch Association for Data Sharing (NEDU) [56]. Consumption of households has the highest peaks between 17:00 and 21:00 and high values in the morning. For farmers, the morning peak will most likely be earlier, between 05:00 and 07:00.

Lastly, irrigation is done, if at all, 5 weeks after the sowing week(s) [55]. If the year is exceptionally dry, irrigation will be done during the driest periods of the growing season. If continuous irrigation throughout the day is not needed, the sunniest hours are avoided, since this prevents crop scorching.

2.3.6. FUTURE ENERGY DEMAND

In this section, assuming a 100% renewable energy mix, technological developments that hold potential for enabling this scenario will be discussed. The tangibility of these developments have been cross-validated in the farmer interviews. To the same end, an extensive study with farmers has been conducted by Wageningen University & Research [51].

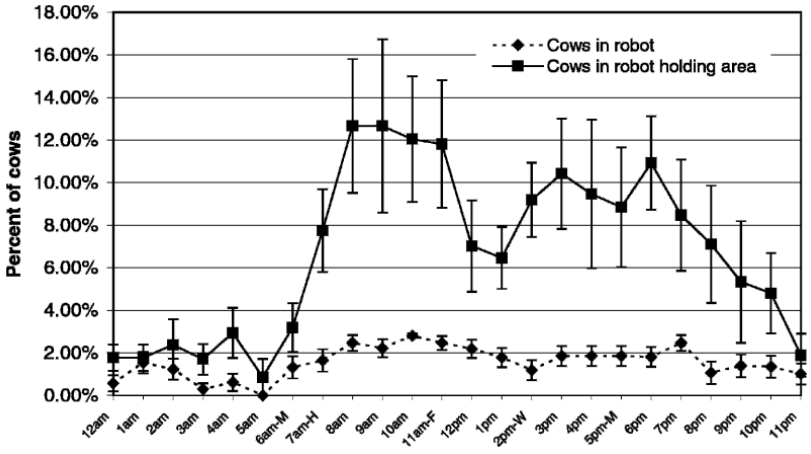


Figure 2.9: Hours during the day when cows are being milked by an automated milking system[57].

A seemingly imminent trend in Dutch farming is automation. The activities for which automation is occurring either in pilot or commercial circumstances are mainly in dairy farming:

- Feeding and feed pushing [58]
- Milking [57]

Automatic feeding uses less energy, since it is not done with a tractor but a more efficient dispatching system[59]. In the Netherlands, 4,679 businesses use milking robots, which is a large portion of the 14,700 dairy farms [60]. Large-scale dairy farming has achieved high levels of automation and generally, organic farming has a higher labor-to-energy ratio [61]. This suggests that intensive, non-organic farms are more inclined towards automation than extensive, small-scale farms. To correlate technological integration with different farm types, a comparison of a range of farm types and scales is shown in the Appendix (for the Appendix, refer to the digital edition).

For the milking process, the periods during the day in which cows are milked by the robot is shown in Figure 2.9. The robot is continuously milking cows, with the exceptionally of its 2 hour cleaning procedure between 3 AM and 5 AM. The pattern in the cows' desire to be milked seem to resemble solar PV generation more than the morning and late afternoon peaks for manual milking. However, automatic milking systems use far more energy (18-39 Wh/kg) than traditional milking parlors (4-17 Wh/kg), so it is not directly evident that a PV system will be able to align better with automated than with manual, as will be discussed in Section 4.5.

For milk cooling, the most immediate and effective technological adaptation is the heat exchange between groundwater for cleaning and drinking and the cooling of milk. Based on the interviews with farmers, it seems that in The Netherlands, it is commonplace to heat the water for cleaning the milking system to approximately 55 degrees Celsius. A smaller effort therefore needs to be made to heat the water to the desired 80 degrees Celsius for cleaning.

As discussed in Sections 2.3.3 and 2.3.2, diesel consumption is currently mainly attributed to field operations and light barn movers. The latter has a demand pattern that aligns with current battery technology: up to 60 minutes of use at around 50 kW requires a minimum of 50 kWh, a sizing that is well within range of current battery development in electric vehicles. It is therefore no surprise that electric forklifts, shovels and light tractors are gaining traction, with large manufacturers pledging to offer electric options for all their small farm vehicles by 2026 [63] and most of the electric farm vehicle market being small farmers with small vehicles [64]. The advent of PV installations on 85% of farms [1]

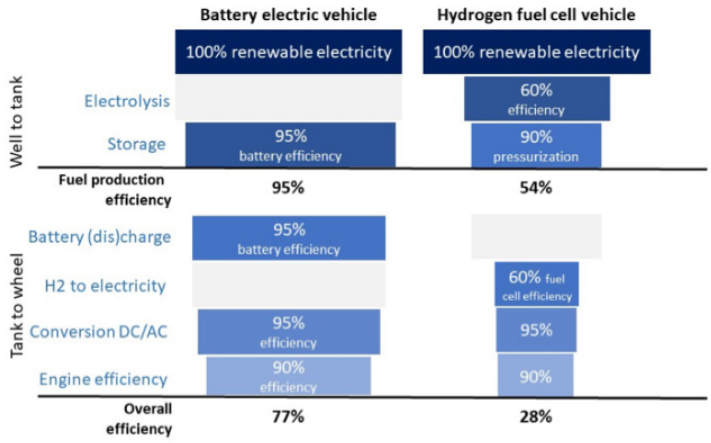


Figure 2.10: Well-to-wheel efficiencies of battery electric vehicles and hydrogen fuel cell electric vehicles[62]

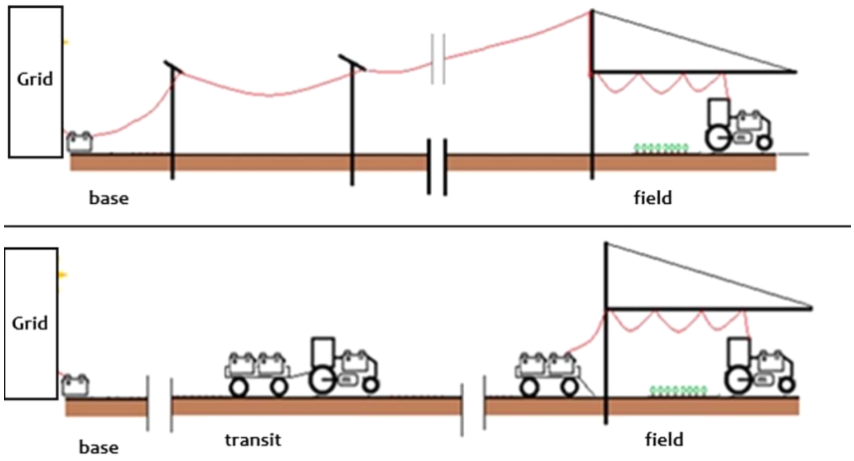


Figure 2.11: Schematics for cable-fed electric tractors. In the source [65], the bottom configuration was calculated to have economic viability compared to conventional tractor O&M costs, whereas the top configuration has infeasibly high investment costs for the transmission system.

makes electric charging an appealing proposition.

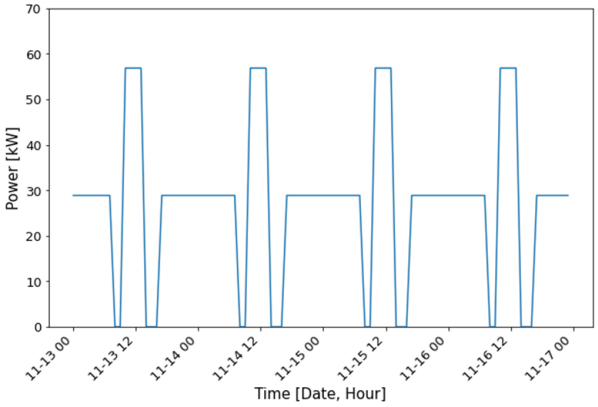
This brings the discussion to the largest bottleneck for the agricultural energy transition: the decarbonization of large tractors for field operations. Tests with electric tractors in The Netherlands, tractors can drive for several hours before the battery runs out [66] [5]. Assuming the largest battery packs currently built for testing (150 kWh [62]), multiple battery switches are required for a single day's operation. Although large farm enterprises are occasionally positive [67], farmers see the uncertainty in the development of charging infrastructure and energy supply as a large concern [68]. Coincidentally, in the same study, on-farm generation of electricity through PV deployment is said to significantly improve farmers' interest in the adoption of electric tractors. In the development of renewably-sourced field tractors, two powertrains are commonly compared: hydrogen fuel cell electric and Li-ion battery electric. The composition of the well-to-wheel efficiencies (term coined for the efficiency from the initial energy source to useful kinetic energy) is shown in Figure 2.10. A second key comparison is the energy density, both volumetric and gravimetric: a Li-ion system's weight is 5 times greater and 200 times larger [62]. These two comparisons are instructive for the trade-off between the two powertrains: where Li-ion battery electric is more efficient, adequate quantities of compressed

hydrogen might be more practically feasible to fit onto a tractor. One way to overcome the volumetric and gravimetric challenge of battery-driven electric tractors is through direct cable feed, a configuration recently emerging in literature [69] [70] [71]. In Figure 2.11, a schematic is shown of two configurations. It is not evident why this practice has not received more academic attention, considering the seemingly insurmountable challenge of supplying heavy tractors with batteries. The challenge will be a practical and economic challenge, but for the simulation of mismatch, the difference between a trolley system and a battery system are marginal. This technological development will therefore not be considered as an option for the model.

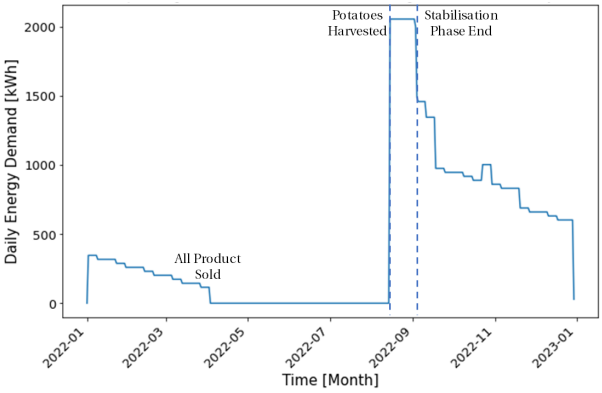
In the model, automation and vehicle electrification will thus be included as scenarios. Besides technological developments on the demand side, there are two more scenarios related to generation and storage that will be included in the model. They are discussed in Sections 4.2.2 and 3.4.1.

2.4. MODEL INTEGRATION

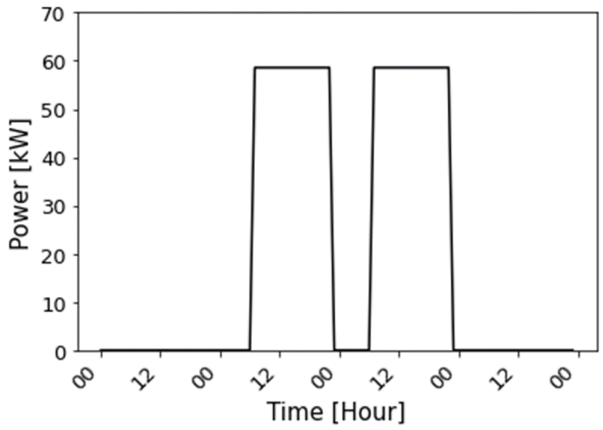
To model a farm's energy system adequately, the findings in Section 2 are translated into day profiles and fluctuate throughout the year. In this section, the underlying assumptions for each load type are provided, and the load profiles are shown in Figures 2.12, 2.13 and 2.14. The assumptions have varying degrees of empirical basis or reference to literature. Refer to Section 2.3 for more direct reference to sources, and to Appendix for the degree of confidence in the assumptions.



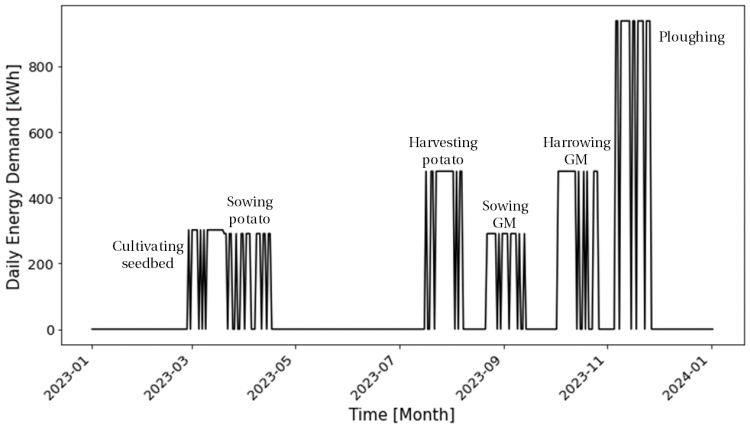
(a) Hourly profile in storage period for potatoes. Cooling occurs during the day, but ventilation is done at night when electricity prices are lower. Scenario where ventilation is shifted to daytime to align with PV generation is discussed in Section 4.4.4.



(b) Energy consumed during a day for storage of potatoes. The first peak in August represents the *stabilisation phase*, after which produce is sold and temperatures drop, which leads to a decrease in energy consumption, up to the point where all potatoes have been sold (April).



(c) Hourly profile of field tractor use. As described in Section **??**, the tractor is ideally operated from dusk till dawn, unless the soil is too moist. It can be seen that operations have been paused to wait for the soil to dry.



(d) Power needed for field operations throughout the year for potato farming. Just before sowing in April, the seedbed is cultivated. Harvesting is done in July/August. Green manure is sowed and harrowed in the fall. Lastlty, before the winter, the first ploughing is done for the next growing season. The timing of these operations varies strongly between farmers depending on climate and soil conditions.

Figure 2.12: Arable-specific load profiles indicating energy consumption on a state-of-the-art potato farm, 60 ha in size.

2.4.1. OPEN-FIELD FARM LOADS

In the following section, the details of the operation time and power demand of the loads for open-field farming will be discussed. In Figure 2.12, the load profiles for the two dominant energy consuming activities are illustrated. Besides having a characteristic hourly profile, the demand throughout the year is also a distinct feature of these loads. For both crop cooling and ventilation and tractor operations, this profile strongly depends on the type of crop (see Section 2.3.2). An important note for the field operation loads in Figure 2.12c is that the load is typically an electric vehicle. This means that the direct electricity demand does not (have to) coincide with the power demand of the

activity.

In the following overview, the details and assumptions from which the simulated loads emerge are provided. The confidence of the assumed specifications in this overview, which resulted from the thematic analysis introduced in Section 2.2, can be found in the Appendix.

CROP COOLING AND VENTILATION

Where Figures 2.12a and 2.12b provided an example of crop storage for potatoes, Table 2.3 provides a comprehensive overview of the parameters of the crop storage process.

- Operation Time: After harvesting is completed, crop-specific cooling and ventilation operations are on 24 hours a day, for the crop-specific duration of the stabilization phase.

Table 2.3: Storage requirements for various agricultural products. The stabilising phase starts when all crops have been harvested. After this phase, cooling stabilises to 6 hours a day and ventilation stabilises to 2 hours a day, assuming that storage capacity is fully in use.

	Onions	**Potatoes**	**Root Vegetables**	**Grains**
Cooling $\left(\frac{W}{\text{ton}}\right)$	100	60-80	100-150	-
Ventilation $\left(\frac{W}{\text{ton}}\right)$	20	20	-	20
Type of stabilising phase	Both	Both	Cooling	Drying
Duration of stabilising phase (weeks)	4	1	6	1-2

  - △ After the stabilisation phase, number of hours is gradually reduced to 2 hours for ventilation and 6 hours for cooling, converging towards noon.
  - △ These values are then proportionally reduced towards 0 on the last storage month (a user input parameter)
  - △ The installed capacity is meant to keep the produce cool at 35 degrees Celsius. Therefore, after stabilization phase, the number of daily hours increases linearly between 15 and 35 degrees ambient temperature.
- Power: See Section 2.3.2
- Stochastics:
  - △ None.

FIELD OPERATIONS

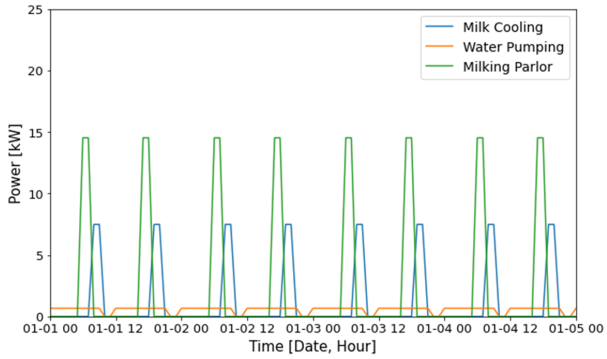
Where Figures 2.12c and 2.12d provided an example, this list describes the load modeling for any field operations.

- Operation Time: Sowing and harvesting periods and any other tillage activities from user input; 07:00 - 21:00.
  - △ Sowing and harvesting periods are assumed for the 27 most commonly tilled arable and vegetable crops based on [35] and other sources
  - △ Total tilling days D_{till} needed is calculated as

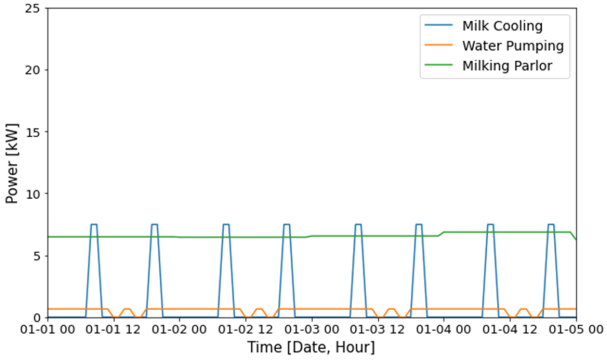
$$D_{till} = \frac{A_{arable}}{W_{impl}} \frac{1}{14 \cdot v_{work}} \tag{2.4}$$

    where A_{arable} is the arable farm area. Furthermore, this determination considers a 14 hour work day, where the working speed of the tractor v_{work} is translated to $\frac{m}{h}$ and the implement width W_{impl} as multiple of 1.5m. This multiple scales with size of farm, starting at 1.5m for less than 40 hectares and adding 1.5m for every 100 hectares.

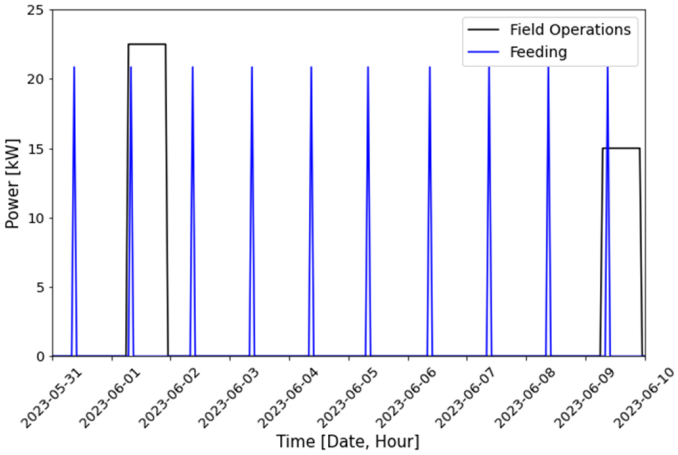
- Power: Depending on task, calculated using Equation 2.1, values derived from Table **??** and assuming permanent magnet synchronous motor efficiency value from [72] (92%).
  - △ Constant power demand
  - △ Soil type is based on crop's preferred soil conditions, divided into clayey, loamy, sandy. Depending on this preference, power demand is multiplied by a factor of 1, 0.86 or 0.69, resp. based on differences in draft force from [37]
  - △ Secondary tillage requires 25% less energy
  - △ For a scenario with batteries, a round trip efficiency of 0.90 was taken
- Stochastics
  - △ Whether a day is suitable for tillage: Bernoulli distribution with $p = 0.75$ (arbitrarily chosen). If no tilling can happen, hours are moved to the next suitable day.



(a) Dairy-specific load profiles for state-of-the-art manually operated farm. Milking is done at 06:00 and 17:00 for two hours, after which cleaning occurs. Off hours of water pumping are chosen randomly and repeated for several weeks.



(b) Dairy-specific load profiles for state-of-the-art automated farm. Automated milking operates continuously, with fluctuations in power consumption. It is assumed that cooling is still done in short bursts as with manual operation and that feeding also occurs once or twice a day.



(c) Dairy-specific load profiles for state-of-the-art field operations for dairy grassland. The field operations are assumed to consist of two activities: mowing and fertilizing. Mowing uses more power than fertilizing. Detailed descriptions of yearly operation can be found in Table 2.4.

Figure 2.13: Load profiles representing assumptions of a state-of-the-art dairy farm with 110 cows. Detailed description of yearly operation is provided in Table 2.4.

2.4.2. DAIRY FARM LOADS

As for open-field in the previous section, the dairy-specific loads will be illustrated and detailed in this section. The illustration is provided in Figure 2.13, where the electric loads for both types of Dutch dairy farms, those with manual milking systems and with automated milking systems, are shown, along with the universal diesel demand for managing dairy grassland. This figures considers the Dutch average of 60 hectares, equating to about 110 full-grown dairy cows.

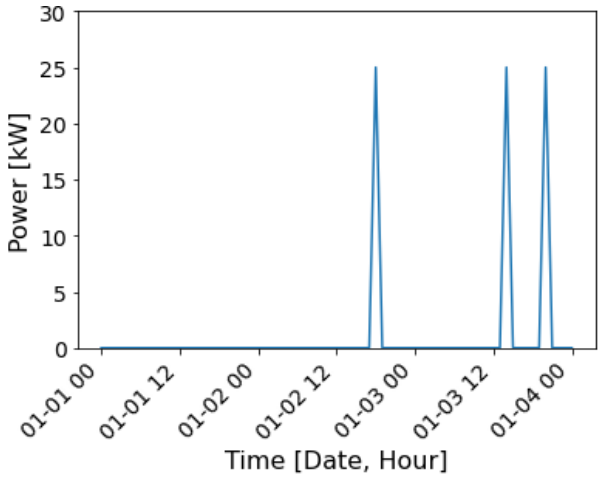
In Table 2.4, the specifications of the load profiles used in the model are provided. All loads are assumed to have a constant power demand when in use. This is, besides some loads like water pumps that occasionally operate with variable frequency drives, a fair assumption. The confidence of the specifications of the loads, as a result of the thematic analysis of the interviews, introduced in Section 2.2, are provided in the Appendix.

VALIDATION LOAD PROFILES

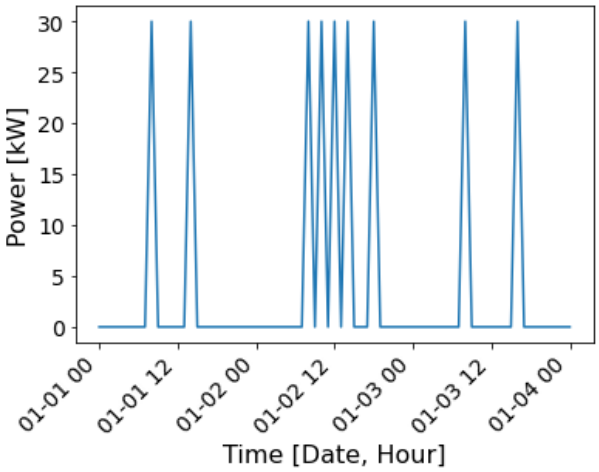
In contrast to open-field, there have been a small number of studies on dairy farm hourly energy consumption. One of these profiles, Figure 2.8, is provided in the discussion in Section 2.3.4. The difference with the model of this study in Figure 2.13a is that the consumption outside of the peaks is higher in Figure 2.8 than in the loads modeled in this study. This can be explained by the decisions to leave out certain loads such as lighting due to their small and uncertain nature.

Table 2.4: Chosen parameters for the load profiles of machines for dairy farm operations.

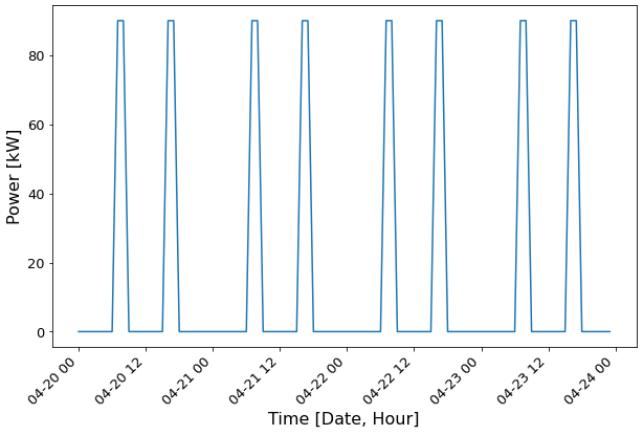
Machine	Operation Time	Power per cow [W]	Stochastics	Clarifications
Traditional Milking Parlor	Daily, two hours, starting at 06:00 and at 17:00	132	Start and end time: Normal distribution σ = 15 min	See Section 2.3.3.
Automated Milking	Daily, continuous	59	Power: Uniform distr. [a,b] = [10.3,10.3]	Uncertainty from [57]
Milk Cooling	Daily, two 1.5 hour windows directly after milking	68		Assuming 8.3 kWh/1000L milk and 9,000L milk per cow. See Section 2.3.3
Water Pumping System	Daily, 16 hours	6	Off hours: Uniform distr. [a,b] = [0,24]	Based on 170L of water consumption per cow per day. The amount of water needed for cleaning is neglected
Feeding	Daily, 1 hour at 8 AM.	350	Starting time: Normal distr. σ = 1 hour	
Fertilizing Field Operations	Every 4 weeks between February and August. From dusk till dawn until all area is covered	$W_{impl} \cdot 10,000$ (TOTAL)	-	According to farmers, fertilizing is not strongly dependent on weather, so no randomness
Mowing Field Operations	Every 4 weeks between May and October. From dusk till dawn	$W_{impl} \cdot 15,000$ (TOTAL)	Suitable Weather: Bernoulli distr. p = 0.75	If weather is unsuitable, the mowing is moved to the next suitable day
Water Heating				Negligible, see Section 2.3.3.
Lighting				Ignored, see Section 2.3.3



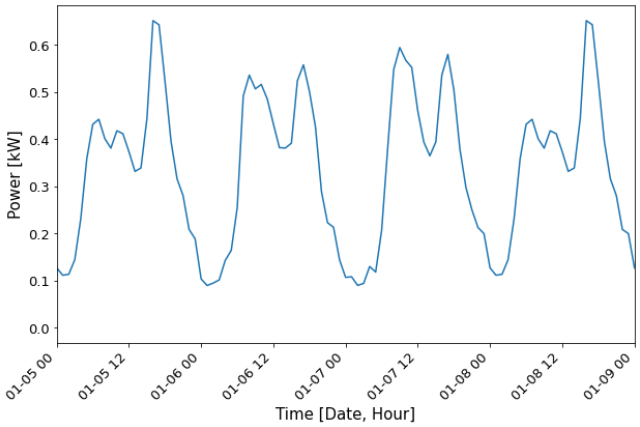
(a) An example four day-period where the car is used for several trips. There is no fluctuating yearly pattern. Number of cars increases with larger farm sizes, not number of trips per car.



(b) An example four day-period in which a light barn mover (forklift, shovel or other) is used for miscellaneous tasks. There is always at least an hour in between tasks for charging. There is no fluctuating yearly pattern.



(c) Example of an irrigation period. The length of an irrigation period is fixed. If the available irrigation reel has enough output per time unit to irrigate the whole area without operating all day, the sunniest hours are avoided to prevent leaf burn.



(d) Typical Dutch household natural gas consumption patterns [56] for four winter days. For simplicity, and because gas is the largest consumer of energy, electricity consumption patterns are not considered.

Figure 2.14: Demand profiles of the four loads present in all farm types. The above two profiles are electric vehicles, meaning that they're demand only indicates when they *cannot* be charged.

2.4.3. UNIVERSAL LOADS

Universal loads can be found in both farm types. Their modeled profiles are illustrated in Figure 2.14 and all loads are described in more detail in Table 2.5. The confidence in the assumed specifications, as a result of the thematic analysis introduced in Section 2.2, can be found in the Appendix (see digital edition). Cars and light barn movers are considered electric vehicles, therefore, the instantaneous electric demand does not have to coincide with the power demand of these loads. As can be seen in Figures 2.14a and 2.14b, the number of trips varies per day and is distributed along a normal distribution, where the mean of the distribution is higher for barn movers than for cars. Although the power demand of the irrigation is high, it is only operated at short periods during the year. In this study, a moderate Dutch level of rainfall is considered (where approximately 35 billion litres of water is used by open-field farming [13]). The farmstead values used were published by the Association for Dutch Energy Data Exchange (NEDU) [56].

Table 2.5: Chosen parameters for the load profiles of universal machines.

Machine	Operation Time	Power [kW]	Stochastics	Clarifications
Car	Length: 1 hour. When: between 07:00 and 21:00	25	Number of trips: Trunc. normal distr. $a = 0; \mu = 1; \sigma = \frac{1}{\sqrt{2}}$	Number of cars proportional to size of farm: 1 for every 100 hectares.
Light Barn Mover	Length: 1 hour. When: between 07:00 and 18:00, random distribution is uniform. Number of tasks: .	30	Number of trips: Trunc. normal distr $a = 0; \mu = 2; \sigma = \frac{1}{\sqrt{2}}$	Number of movers proportional to size of farm: 1 for every 60 hectares.
Farmstead	Typical Dutch household consumption profile [56]	27 [kWh/year] Scale: 60 ha : 1 household	-	Current gas consumption is converted to electric units and added to electricity consumption [73]
Irrigation	5 weeks after each sowing period. Number of hours a day: depends on weather and land area	30	-	Weather is set as parameter, no stochastics

2.5. CONCLUSION

Chapter 2 establishes the energy demand profiles for farms, highlighting the significant variation due to seasonal activities and varying levels of electrification. This analysis is essential for understanding the energy requirements of agricultural operations, which serves as a foundation for optimizing energy systems in later chapters.

3 | PV System Modeling

3.1. Introduction

In the previous Chapter, the first objective of this study was addressed: researching and modeling the hourly profiles of the energy demand on dairy and open-field farms. In this Chapter, a step towards the second objective, quantifying and optimizing the matching of energy demand and solar PV generation, has been taken.

The aim of this step is to integrate solar PV generation into the model. To this end, reliable and realistic PV yield profiles for the generation side of the simulation have been developed and are discussed in this Chapter.

In Section 3.2, the methodology for modeling solar PV yield profiles is discussed. In Section 3.3, a set of three profiles is chosen for integration into the model and their universality are studied. This is done through a sensitivity analysis of the yield to changes in the parameters of the PV architecture. Lastly, in Section 3.4 the integration of the solar PV profiles into the energy system model is discussed.

3.2. Methodology

In this Section, the methods for selecting and integrating solar PV yield profiles into the model are discussed. The topic to be addressed first is how irradiance data is used for modeling PV yield. After this, the different computational tools are compared, after which the chosen tools are discussed. The approach for determining the sensitivity of the simulations is then illustrated.

3.2.1. Irradiance Decomposition Models

Irradiance data from measuring instruments are not yet suitable for computation. Therefore, before simulations of solar irradiance can be executed, the measurement data must be decomposed into suitable components.

Irradiance data can be measured using a combination of pyranometers, pyrheliometers and albedometers. This data comes in the form of the Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), and Global Horizontal Irradiance (GHI), which are related as follows for a horizontal surface:

$$GHI = DHI + DNI \cdot cos\theta_z \tag{3.1}$$

where θ_z is the solar zenith angle, which is the angle between the direction of the Sun's rays and the normal vector of the horizontal surface. For analysing diffuse incident irradiance, these components must be split into components that describe its complex distribution more accurately. TNO's modeling tool BIGEYE, which is discussed in the following section, uses a common decomposition model known as the Perez model[75]. For this model, the irradiance is split into the following components:

- Direct beam
  - △ Equal to the DNI.
- Circumsolar
  - △ Brightening effect that is strongest near the middle of the Sun, but excluding the DNI. Falls off in intensity farther from the Sun.
- Isotropic
  - △ Component uniformly distributed over the entire sky dome.
- Horizon Brightening

△ Component consisting of the warmer colors (500-700nm) reaching the surface near the horizon because light passes through the atmosphere for a longer distance. Because of this distance, low energy photons experience Mie scattering while the high energy photons experience Rayleigh scattering. So although it is called brightening, the energy is lower.

The components are represented graphically in Figure 3.1.

3.2.2. IRRADIANCE MODELS

The different types of computational methods for modeling irradiance are now discussed. Though there are many models to describe fluxes such as irradiance, including Discrete Ordinates Method and Finite Elements Method, PV system yield modeling is typically studied using either a *transposition model, ray tracing model* or *3D view factor model.*

TRANSPOSITION MODELS

Transposition models determine irradiance by adding beam, diffuse, and ground-reflected sunlight on a plane, such as a solar module, known as the Plane of Array (PoA) [76]. The computation is fast and is accurate for calculating direct irradiance. The accuracies of the diffuse and reflected components are limited, however. This inaccuracy is further increased, because for transposition models it is assumed that the ground is illuminated uniformly and its reflectivity is constant. Transposition models are therefore fast but have lower accuracy, suitable for monofacial PV modules in open landscapes, but not for more complex systems such as agrivoltaics.

RAY-TRACING MODELS

Ray-tracing (RT) models trace rays between the light source and the relevant surfaces [77]. RT models are comprehensive but computationally intensive. They make it possible to accurately model any surface geometry in any orientation and include bidirectional scattering distribution functions, as is the case in urban areas, where surfaces are not always flat and nearby structures strongly impact incident irradiance [78]. Developments in ray-tracing are making it more efficient, such as backwards RT and decoupling optical material properties and illumination conditions [79].

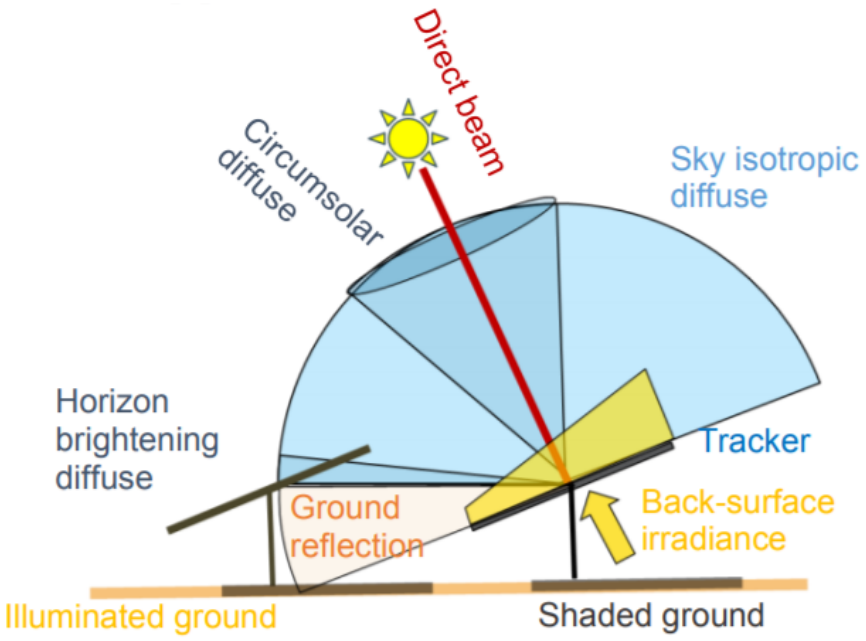


Figure 3.1: Components used in Perez irradiance modeling [74].

While RT models offer flexibility, because of the repeated calculations throughout the simulation, spectral resolution and time-varying optical properties are conventionally omitted, both essential for bifacial PV, and therefore agrivoltaic, systems[80]. Adding these capabilities to RT models is computationally burdensome. In contrast, transposition and view factor models can easily incorporate these features. In addition, spectral resolution will be indispensable with the advent of tandem PV modules [81], making this functionality all the more important in PV modeling.

VIEW FACTOR MODELS

Lastly, 3D view factors are a commonly used method for modeling irradiance. In view factor modeling, the *visibility* of each surface with respect to other surfaces is computed. The view factor is a value between 0 and 1, where 0 means the surface cannot 'see' the other surface and 1 meaning that they are parallel to one another.

In Figure 3.2, examples are shown of two surfaces and the relevant components for determining the surface's view factors. On the left, the relevant vectors and angles are shown, used to determine the view factor as follows

$$F_{i\to j} = \frac{1}{A_i}\int_{A_i}\int_{A_j} \frac{cos\theta_i cos\theta_j}{\pi s^2} dA_j dA_i, \tag{3.2}$$

where $F_{i\to j}$ is the view factor of surface i with respect to j. With this calculation in mind, the middle depiction must have a VF larger than zero, meaning that they are facing one another. On the right, the surfaces do not in any way 'see' each other, so the VF is zero.

Computing 3D view factors requires only one initiating analysis for the chosen geometry, as opposed to iterative tracing of rays in RT models, and is therefore computationally more efficient. In the context of agrivoltaics, where accuracy and computational efficiency are desirable, 3D view factor models are often favored due to their balance between speed and accuracy. They offer fast but accurate modeling, making them suitable for simulating irradiance in agrivoltaic systems. A summarizing comparison of the systems is provided in Table 3.1.

Model Type	Computation Time	Spectral Resolution Feasible	Accuracy for Complex Geometries
Transposition	Low	No	Low
Ray-Tracing	High	No	High
3D View-Factor	Medium	Yes	High

Table 3.1: Comparison between irradiance models. The BIGEYE tool agrees with the 3D View-Factor features described here.

3.2.3. BIGEYE

For the reasons mentioned above, TNO's software tool BIGEYE, the tool used in this study, is based on 3D view factors to determine incident irradiance on arbitrary geometries. BIGEYE differentiates its

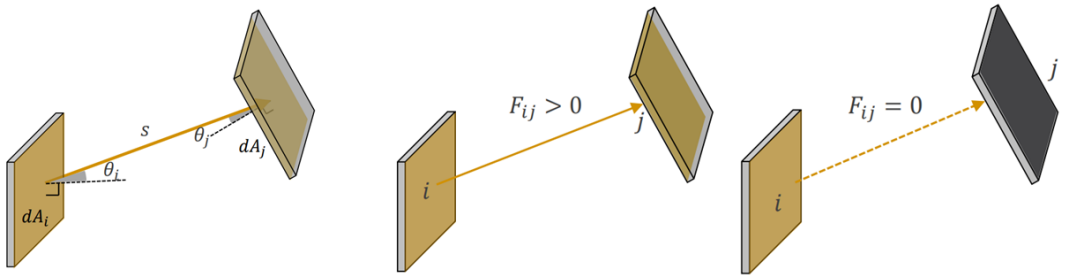


Figure 3.2: Three representations of two surfaces[82]. The left example depicts the relevant vectors and angles for calculating the view factor as in Equation 3.2. The other two indicate their view factor with respect to each other.

approach to conventional 3D view factors by setting thresholds to the computation of view factors [83]. In other words, if the distance between surfaces s is several times larger than the infinitesimal surface sizes, the view factor is not calculated. Additionally, the size of the surfaces, where the map of surfaces is known as the mesh, is adapted to the relevance of the geometry. Surfaces on or near the solar array are smaller to retain accuracy and surfaces farther away are larger to save computation time.

With GHI data as input, BIGEYE uses the Perez irradiance decomposition model to separate the irradiance components described in Section 3.2.1. To determine the effectiveness of the solar modules in converting the irradiance to electric power, a thermal model is integrated. The temperature difference is a function not only of the front and rear incident irradiance $G_{fr,POA}$ and $G_{re,POA}$ but also the thermal coefficient specific to the geometries of the system U_c. The wind speed-dependent thermal coefficient, U_v is not considered, as is common in PV modeling software due to unreliable data on wind velocities [84]. With T_{cell}, and the addition of mismatch considerations at the cell, module and system level, the deviation from module performance at Standard Testing Conditions (STC) conditions can be determined.

3.2.4. SENSITIVITY ANALYSIS

In this study, several PV system architectures were chosen for the full energy system model, presented in Section 3.3. To determine how sensitive the yield is to the parameters of the systems, a sensitivity analysis was conducted. The analysis was done by making incremental changes in the PV system parameters, such as tilt angle and pitch, to determine their significance for the optimization of the mismatch, when compared to the uncertainties of the energy demand values and to a lesser degree the uncertainties of the PV modeling itself.

Since this analysis was done without integration into the energy system, the sensitivity is not directly between the power mismatch and the PV system parameters. The sensitivity analysis is therefore not directly related to the objective function of the system, but only to the PV yield.

3.3. RESULTS

In this Section, the PV systems that will be modelled and matched in this study are discussed. Thereafter, to judge whether the chosen parameters provide a representative yield for the given system, the outcomes of the sensitivity analysis are discussed.

3.3.1. PV SYSTEM BENCHMARKS

The system architectures chosen as benchmarks for this study are:

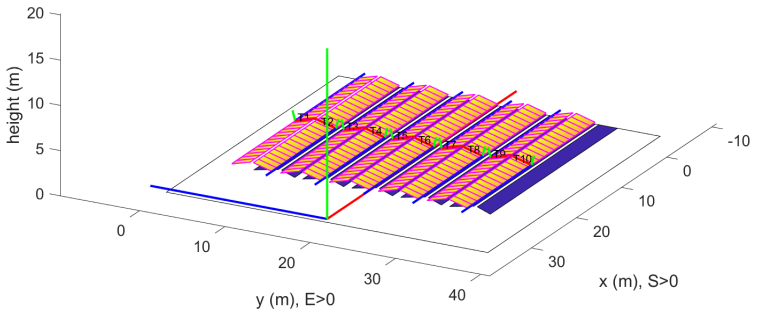
- Vertical
- Single-axis tracking (SAT)
- Stilt-mounted fixed dome

In Figure 3.3, the geometric MATLAB models used for the BIGEYE simulations for these three systems are shown. They have been selected on two grounds: the type of systems in current pilot projects in The Netherlands [85][86][87] and which systems are commonly benchmarked in literature [19][20][21][88][89][90] (to name a few).

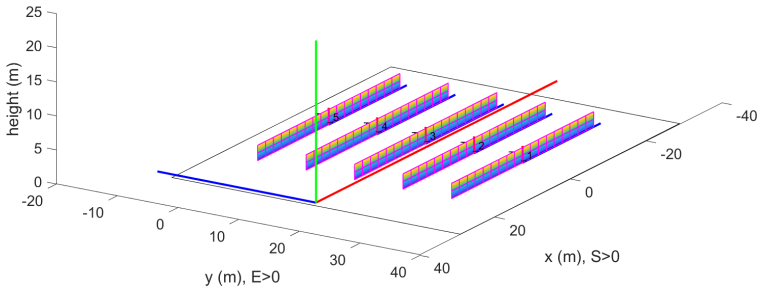
As is often the case in both practice and theory, the vertical system has two panels stacked on each other, with no space in between. The SAT system follow the Sun elevation, and employs a back-tracking algorithm. This prevents detrimental inter-row shading. The stilt-mounted fixed dome is dimensioned so machinery can operate normally.

PV MODULE

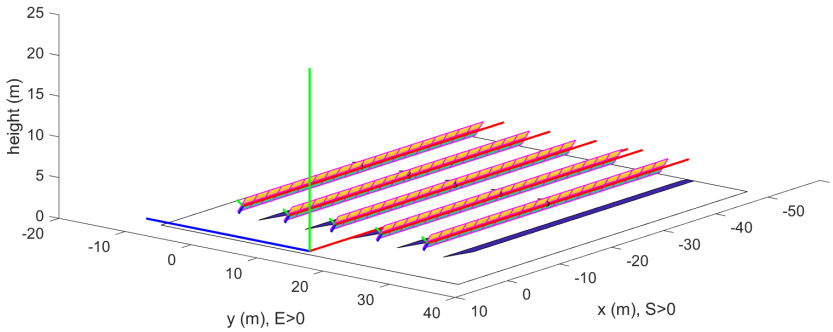
In the comparison of yield profiles, the PV module used will be identical, unless the system is designed for different module characteristics. For example, there is a limited numbers of crops that would grow



(a) Fixed-tilt dome system



(b) Vertical system



(c) Single-axis tracking system. other angle and indicate that this is just one discretization

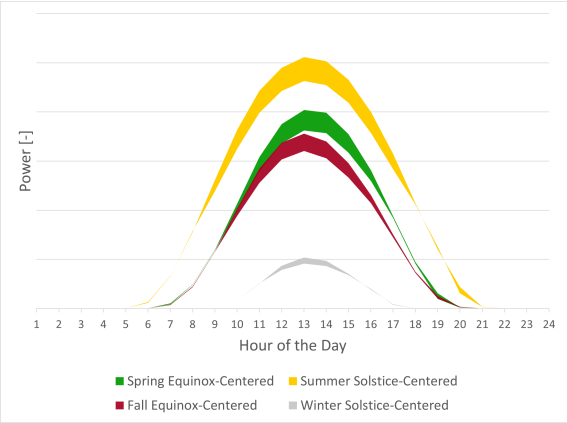
Figure 3.3: The three chosen system architectures to model. Positive x-direction points to the South (S>0) and positive y-direction points to East (E>0). The parameters are based on findings from the sensitivity analysis done in Section 3.3.2.

under a fixed-tilt system with non-transparent PV modules [91]. Even more Sisyphean would be to use semi-transparent PV modules in an SAT system, since the effects of transparency and the tracking would negate one another in terms of PV yield, and the effects on crop growth are ambiguous [92]. The fixed-tilt dome system will therefore use a semi-transparent module and the other two will use a non-transparent module.

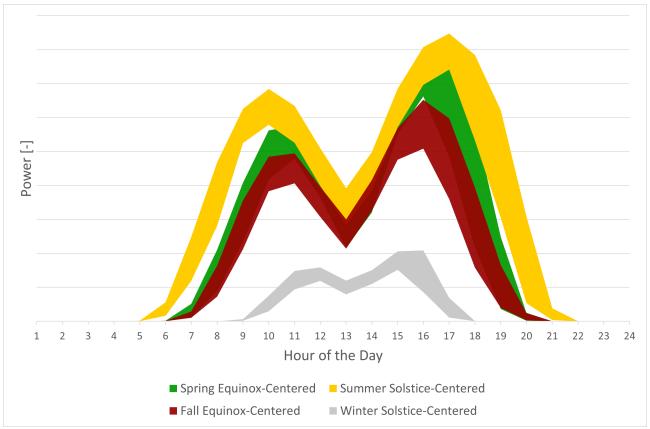
In choosing a module, two other important considerations are the expected market shares and performances of emerging cell technologies. Considering TOPCon's Compound Annual Growth Rate of 23.5% [93], high efficiencies and technological overlap with the current dominating cell technology, PERC, [94] a TOPCon module was chosen that correctly considers front and back side yield at STC in determining the bifaciality factor. The module performance under different temperatures, currents and voltages for both (transparent and semi-transparent) chosen modules are shown in the Appendix (for the appendix, refer to the digital edition).

3.3.2. SENSITIVITY ANALYSIS

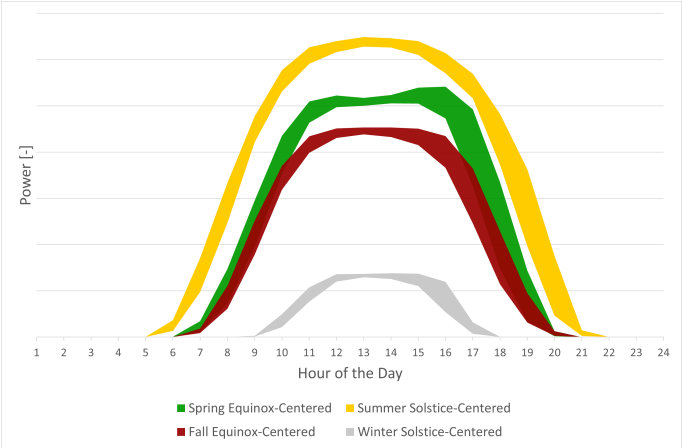
As preluded in Section 3.2.4, the effect of changing the parameters of the chosen PV system architectures is analysed. First, to determine which parameters significantly altered the PV yield, all parameters were coarsely iterated over. Then, simulations were run over the feasible range of the selected parameters. The range of outcomes of these simulations are shown in Figure 3.4. As mentioned in Section 3.2.4, the 'seasons' are centered around the equinoxes and solstices, in order to amplify the differences in yield throughout the year.



(a) Power values for tilt angles of a fixed-tilt dome system between 0 and 30 degrees. The highest power values are for a tilt angle of 15 degrees and the lowest values are found when it is 30 degrees.



(b) Power values for pitch distances of a vertical system between 4 and 12 metres. Two peaks instead of one, characteristic for vertical systems, can be seen. Values in the equinox periods are relatively high compared to other systems.



(c) Power values for pitch distances of a single-axis tracking system between 4 and 12 metres Thanks to optimal tracking, the peak values during the day are extended.

Figure 3.4: Sensitivity analysis of the power yield of the chosen system architectures. The actual power values are left out, since the figures are meant to illustrate the difference between periods in the year. The difference between actual power values of the different systems would be misleading, since the unit rows used in the simulations are different sizes.

FIXED-TILT DOME PV SYSTEM

For the fixed-tilt dome system, it was concluded from the initial bearings that the tilt angle and module transparency had a noteworthy effect on the PV yield profile. Modifying minimum module height and distance between rows, known as pitch, had little effect. Changing the transparency for the module involved linear optimization. The voltage and power values of the module were adapted. The IV curve was then fitted using a linear solver to find suitable single-diode parameters.

In Figure 3.4a, the sensitivity to varying the tilt angle is shown. From the Figure, it can be seen that the differences are strongest at the peak PV yield hours. The lowest values are from simulating a system with a tilt angle of 30 degrees. It is only during the winter solstice period, when the sun elevation is lowest, that the high tilt angle does not have a diverging yield from the simulation with 15 degrees. In the simulation results, it could be found that the diffuse incident light was higher for 0 degrees than for 30 degrees. This can be explained by the fact that a horizontal panel is oriented optimally to receive

diffuse light from the entire sky dome. However, the case of 15 degrees appears to find an optimal balance between diffuse irradiance and a favorable angle of incidence with direct sunlight.

VERTICAL PV SYSTEM

In the case of the vertical PV system, initial exploration of parameters indicated that the distance between the panel rows, known as pitch, had significant influence on the PV yield. The only other adjustable parameter, the distance from the ground, led to no significant alteration of the yield.

Therefore, a range of simulations was done with different pitch values, shown in Figure 3.4b. The PV yield is shown to be proportional to the pitch. In other words, the lowest power values correspond to lowest pitch values and the highest power values correspond to highest pitch values. The vertical system has two peaks, with a local minimum when the Sun is highest. When the Sun is high, the angle of incidence on the module surface is the most unfavorable for transmission into the module. This dual peak could be aligned to the energy consumption patterns of dairy farms seen in Figure 2.13a. However, cows are typically milked 12 hours apart, and only in the summer there is significant PV yield 12 hours apart. It can also be seen that the yield in the equinox periods is closer to the summer yield than for fixed-tilt, which is favorable for every type of demand pattern. The effect of the pitch is also more significant, especially for the fall equinox. From farmer interviews, it was mentioned repeatedly that aesthetics and animal welfare strongly favor high pitch distance, making a high pitch distance desirable for both developer and farmer, were it not for the prioritization of intensive land use. This leads to the acknowledgement of the notably wide range of pitch values that was simulated. To justify this wide range, it will be instructive to introduce the concept of *ground coverage ratio* here. The ground coverage ratio is the ratio between the total area of solar panels and the total land area:

$$CGR = \frac{A_{solar}}{A_{total}} \tag{3.3}$$

where A_{solar} is the area covered by solar panels and A_{total} is the total area. In the context of typical ground-mounted solar farms, the goal is simply to maximize this ratio, constrained by the effect of shading between rows of panels: inter-row shading. In the context of agrivoltaics, the trade-off between values for this ratio is more complex, because balancing the PV and crop irradiance, creating microclimate, considering aesthetics and managing soil and water quality are all relevant in determining the pitch.

In this context, this study considers a zero-behind the meter farm, where the goal of the PV yield is to cover the consumption. Since the area needed for this goal is an order of magnitude smaller than the area needed for farming, area is therefore not a limiting factor. This is also the reason why no attention is paid to the irradiance that reaches the crops in this study: the assumption is that there is more than enough. To conclude, the wide range of pitch values was chosen to address the wide decision range for an optimal vertical PV system in the context of a zero-behind-the-meter farm.

SINGLE-AXIS TRACKING SYSTEM

When finding initial bearings on the parameters for an SAT PV system, it was concluded that the pitch and the discretization steps of the system have the strongest effect on the PV yield profiles. In Figure 3.4c, the sensitivity of the output to varying the pitch is illustrated. The extended peak period of this yield in comparison to Figure 3.4a is characteristic of a SAT system, since it can retain the optimal incidence angle during hours of high Sun elevation by tracking. Despite the same wide range of pitch values as Figure 3.4b, the effect on the power output is less significant. This suggests that row shading plays a smaller role for single-axis tracking than for vertical systems.

As with the other figures, it is telling of the Dutch climate that the fall equinox period has lower yield, despite having astro-geometrically identical patterns to the spring equinox. Warmer temperatures in the first months and the sequential cloud coverage in the fall can explain this difference.

3.4. MODEL INTEGRATION

One of the three profiles can be selected when modeling an energy system. The size of the PV depends on the size of the farm. Therefore, in this Section, the sizing of the PV system is discussed.

3.4.1. PV SYSTEM SIZING

In this Section, the sizing of the PV system with respect to the other system components will be discussed. In a typical ground-mounted, mono-functional solar park, the available area will be exploited optimally for PV power yield. Since the aim of this study is to evaluate the suitability of agricultural energy systems for electrification, without reinforcing the grid, the main criterium for the PV system sizing is to minimize grid exchange.

For an small- and average-sized farmers, this means a net grid exchange of at most 3x80 Ampéres: the largest three-phase current allowed for a small-scale grid connection [95]. Enterprises that use more than this current are categorized as large-scale energy users, and other tax regulations apply that are unfavorable for small and average-sized farmers [12].

If 3x80A is the largest connection, this means the optimal sizing for a PV system can be determined as follows:

$$P_{opt,PV} = \frac{\sqrt{3}V_{l\to l}\cdot I_{AC}}{F_{top-off}} = \frac{3V_{l\to n}\cdot I_{AC}}{F_{top-off}} \tag{3.4}$$

where $V_{l\to l}$ is the line voltage at 400V, $V_{l\to n}$ is the more commonly known neutral voltage, which is 230V for Dutch small-scale grid connections.

$F_{top-off}$ deserves further clarification. It symbolizes the chosen *clipping factor*. In most Dutch PV projects, the maximum output of a PV system is capped at 70% of STC peak power. This is done to keep grid connections and cables to affordable sizes, since the amount of energy lost when the output is > 70% of peak power is economically less valuable than the increased costs of grid and cable costs. In other words, the suboptimal operation of solar modules is outweighed by the optimisation of the installed capacity of the grid side.

Going even further, a study by TNO in collaboration with the Netherlands Environmental Assessment

Grid Capacity/ Solar Wp[%]	Unused Energy [%]			Capacity Factor [%]		
	Vertical	Dome	SAT	Vertical	Dome	SAT
100%	0	0	0	10	11	14
85%	0	0	0.7	11	13	16
70%	0.5	1.1	3.9	14	15	19
55%	2.8	5.0	11	18	19	23
40%	9.3	15	24	23	24	27
25%	25	34	44	30	29	31

Table 3.2: The effect of introducing a cap to the power from the solar PV system. The clipped power, as it is referred to, is shown as a percentage of STC peak power. Unused energy yield increases progressively with respect to the clipped power. Although energy is unused, the capacity factor, representing the optimal use of grid capacity, increases threefold for all systems. The capacity factor can be used for determining the performance ratio (PR) and return on investment (RoI).

Agency (PBL) indicates that it makes economic sense to have a grid connection with as low as 45% of the STC peak power of solar modules for a south-facing, ground-mounted system [96]. Having even lower ratios is currently not economically optimal, but still considered viable depending on the context. In Table 3.2, the unused energy due to clipped power is shown. The trade-off to be made is between the reduced costs on the AC-side (inverter, grid management costs and grid electricity bill), increased DC-side costs (module and mounting costs), but is outside the scope of this study. Keep in mind that an energy storage system can create value from this unused energy. Clipping can not only reduce economic costs, but the societal costs suffered from grid congestion due to high demand for

grid reinforcement alongside inefficient cable use (low capacity factor) can also be lightened. The results of simulation scenarios with different clipping factors are discussed in Section 4.4.4.

3.4.2. CAPACITY FACTOR

It would not be correct to state that the three benchmarked systems deliver the same amount of energy. When the same panels are used, the PV system architecture and the size of the grid connection strongly influence how much of that panels peak power can be converted to energy. A helpful metric for this is the *capacity factor C*. It is defined as the total annual energy yield as a fraction of the maximum possible output of the system, which in the situation in which all PV goes to the grid, as in [96], can be defined, in kWh, as

$$C = \frac{\text{Total Annual Energy Yield}}{\text{Maximum Possible Yield}} = \frac{\sum_{t=1}^{8760} P_{\rightarrow grid}(t)}{\sum_{t=1}^{8760} P_{max,grid}(t)} \tag{3.5}$$

where $P_{\rightarrow grid}(t)$ is the hourly delivered power to the AC connection and $P_{max,grid}(t)$ is the maximum hourly allowed power through the grid connection. In Table 3.2, the capacity factor for the different systems is shown in the case of a utility solar system. It can be seen from these values that the SAT system yields the most energy for each installed module. This means it is the most efficient system with respect to the number of modules. Nevertheless, since the materials needed and the costs of the systems are different and dependent on many factors, its high capacity factor does not mean it is always the optimal choice. This is an economic and circumstantial trade-off. Interestingly, the differences between capacity factor diminishes when the clipping factor is high, implying that the bases of the profiles are more similar than the shapes of the peaks.

3.5. CONCLUSION

Chapter 3 focuses on the generation profiles of solar PV systems, showing how different system configurations and their parameters impact the yield. The chapter's insights into solar energy potential and variability are crucial for designing PV-powered agricultural energy systems.

4 | Energy System Modeling

4.1. Introduction

In this Chapter, the building blocks of the energy system model will be pieced together and used for simulation state-of-the-art and hypothetical energy system scenarios. In Chapter 2, the profiles of the main energy consuming activities were drafted. In Chapter 3, on-farm solar PV profiles were generated using BIGEYE. The energy system model brings the demand, as an assembly of loads generated based on user input, together with generation, consisting of the chosen PV profile and grid exchange, and outputs data and insightful data visualisation.

The following Section delineates the operation of the energy system model. First, the fundamentals behind the optimization model are discussed. It is then discussed how the potential of storage technologies are formalised in the model. The high-level model structure is then described. This is done with a workflow of the model, including the execution procedure of the model, known as the formalisation. Then, the implementation of robust optimization and the input parameters of the model are provided. The results in Section 4.3 address the final research question of this study, which were introduced in Section 1.2:

1. If all loads on open-field and dairy farms become electric, how are 1) the energy self-sufficiency and 2) grid capacity needs affected?
2. How can a) load shifting, b) power clipping and c) energy storage on an electric farm's 1) maximize self-sufficiency and 2) minimize grid capacity needs?

These questions are addressed by providing an extensive discussion of simulations done for state-of-the-art farm scenarios, followed by experimentation with different technology scenarios.

4.2. Methodology

In this Section, the mathematical optimization methods underlying the model are introduced. Additionally, the method for determining the potential of energy storage for the system is described. Once these underlying theories have been discussed, the operation of the model from a user perspective will be described. To this end, the workflow, the model execution steps and the input parameters will be discussed. Due to its length, the detailed dissection of the model is accommodated in the Appendix (for the Appendix, refer to the digital edition).

4.2.1. Linear Programming

In this Section, the mathematical and computational methods used in the energy system modeling are discussed. To this end, the chosen optimization methods and software will be discussed.

The aim of the model is to determine the optimal dispatch for the smallest mismatch in an energy system with a modest number of components. To this end, the system was translated to a linear programming (LP) problem. An LP problem consists of *decision variables* and an *objective function (OF)*, subject to a mix of or either *inequality or equality constraints*. Decision variables are the variables in the model that are not fixed, such as the power extracted from or provided to the grid. The constraints either provide a range of possibilities for one or more decision variables to lie within (inequality) or constrain a set of variables to a fixed value (equality). The combinations of decision variable values possible within the constraints is known as the 'decision space'. The objective function in an LP problem reflects the goal of the model and is either minimized or maximized. For the case in point, the objective function (OF) is defined as

$$\text{Minimize: } J = P_{in,grid} + P_{out,grid}, \tag{4.1}$$

where $P_{in,grid}$ is the extraction of power from the grid, and $P_{out,grid}$ is the surplus of the system that is provided to the grid. Since the goal is to enable self-sufficiency and therefore optimal use of the grid,

the two variables of the OF are not weighted. They are of equal weight, since their balance is assumed to allow for more optimal use of the grid.

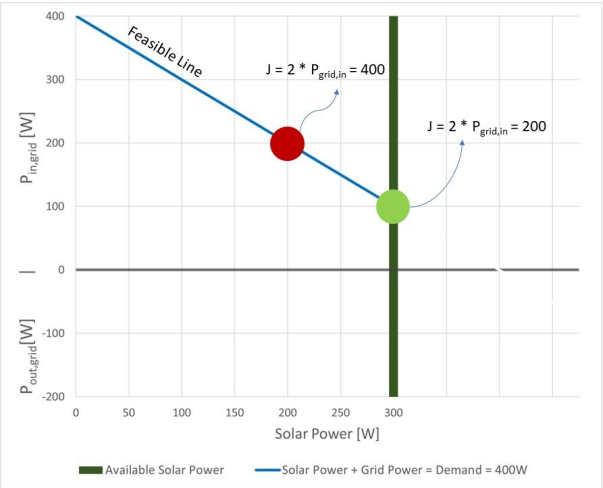
The corresponding decision variables are the in- and outflows of the energy sources, sinks and storage components of the system. The constraints are various, including the capacities of storage components, maximum ampacity through cables, etc.

To illustrate how the mismatch is optimized in this LP problem, the example of introducing a battery in a simple energy system is described. The system consists of a load, solar PV array and a grid connection that can deliver and receive power. Since the OF (Equation 4.5) aims to minimize grid exchange, the optimal solution will be for P_{grid} to get as close to zero as possible within the constraints. In Figure 4.1a, a decision space for this system is shown. We assume a fixed demand constraint (an equality constraint). The two decision variables are the solar power and the grid power used to supply the demand. In this case, the demand is larger than the available solar power. The available solar power limits the OF from becoming zero, and the optimal solution falls upon the lowest OF outcome possible: on the intersection between the two constraints (the vertex). The process of finding this value is typically done using a Simplex method. With this method, the OF value for a randomly chosen vertex is calculated. The values at the neighboring vertices are then also computed. If a neighboring vertex has a more optimal outcome, the computation repeats at that vertex, until a vertex is found whose neighbors do not improve the outcome.

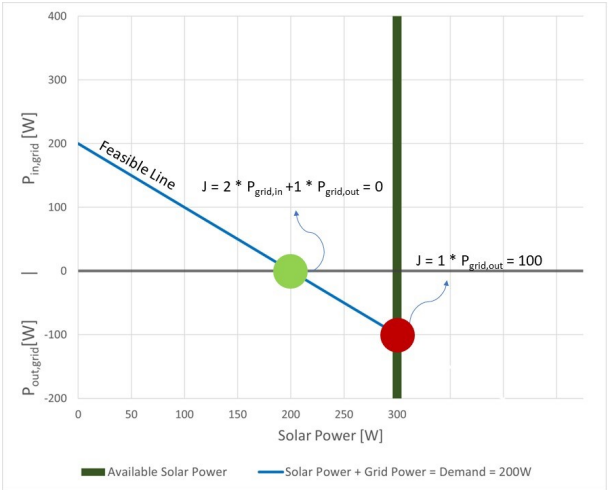
Now in Figure 4.1b, it is vice versa: the available solar power is larger than the demand. This causes the optimal solution to shift. The reason it does not simply shift to the new vertex of the same constraints is because there are two 'hidden' constraints in this situation: $P_{in,grid} \geq 0$ and $P_{out,grid} \leq 0$. This shows that the optimal solution will always be found at a vertex, but since there are multiple, the OF for multiple vertices must first be computed. The constraints that contain the optimal solution in their vertex, are known as the *active constraints*: if their boundaries change, the optimal solution changes. This relation is referred to as the *sensitivity* of the optimal outcome to changes in a constraint boundary. For inactive constraints, the sensitivity is zero. In Section 3.3.2, a sensitivity analysis is conducted for the parameters of the chosen solar system.
In Figure 4.2, a battery is introduced into the system. The battery can discharge or charge any amount of its current capacity within the time step of this problem. With the battery introduction, an *inequality* constraint has been added, creating a feasibility *region*, as opposed to a line in the previous case. The optimal solution is now found in a different intersection of constraints, where P_{grid} *can* be minimized further, in this case to zero.

In the following step, the dynamic complexity of optimizing the dispatch of an energy system becomes truly apparent. The question now is: does the solution in Figure 4.2 remain optimal, when considering all timesteps? Discharging the battery in this example to obtain $J = 0$ is the optimal decision, but if we now introduce an upper boundary for the power delivered by the grid connection, and in the next time step, the demand is greater than this boundary, the battery will not be able to support this shortage and there will be no feasible solution at all. Optimizing a time-based energy system therefore demands analysis of optimality conditions for all timesteps simultaneously.

This demonstrates the fact that this model is optimisation *in hindsight*: the optimal dispatch is calculated, given the information of all timesteps, making it a *acausal system*. This is different from real-world systems, which can only rely on past data (*causal*).



(a) Decision space for a system with decision variables P_{grid}, $SolarPower$, subject to: Solar Power< $300W$; Solar Power $+P_{grid} = 400W$, with objective function (OF) as in 4.5, where x is set to 2. Two points and the corresponding value of the OF are shown. Every combination along the feasibility line is possible, but the optimal solution, i.e. the lowest OF value, is in the intersection of the constraints.



(b) Same decision space as Figure 4.1a, but with a modified constraint: Solar Power $+P_{grid} = 200W$. Strictly speaking, the optimum here still lies on a 'hidden' intersection between the demand constraint and the following constraints: $P_{in,grid} \geq 0$ and $P_{out,grid} \leq 0$.

Figure 4.1: Linear Programming Problem for two scenarios: 4.1a, the demand is greater than the available solar power and 4.1b, the available solar power is greater than the demand. Cable ampacity and conversion factors are ignored.

SOFTWARE FRAMEWORK

To model an energy system as an LP problem, the chosen software framework is the Open Energy Modeling Framework (OEMOF) [97]. Specifically, the OEMOF.solph library was used, which is an open-source framework for modeling and optimizing energy systems using linear programming. It provides the building blocks to design and analyze complex energy systems, with high levels of modularity. It translates the system into a linear programming problem. The inflow and outflow of the modular energy system components constitute the decision variables. The weights and variables of the objective function are determined by attributing variables costs to the in and outflows of the OEMOF energy system components. This study does not consider costs, so the variable costs inputs are used as arbitrary weights for the objective function.

4.2.2. THE NECESSITY OF STORAGE TECHNOLOGY

In this section, it is discussed how the model can be used for suitable sizing of storage technology.

The energy generation and consumption in the modeled systems, using the approach described in the previous sections, will not be perfectly aligned. To reduce this mismatch, the following four tactics can be deployed:

1. Diversification of energy sources
2. Demand side management
3. Short term storage
4. Long term storage

Studying 1) other energy sources and 2) behavioral psychology and economics of energy consuming activities lie outside of the scope of this study. Therefore, for this study, attention will be focused on the last two tactics: implementing storage.

In a paper by Mulder [98], a definition was proposed for 1) short term storage demand and 2) the potential for remaining surplus to be converted to a molecular state (hydrogen and ammonia are

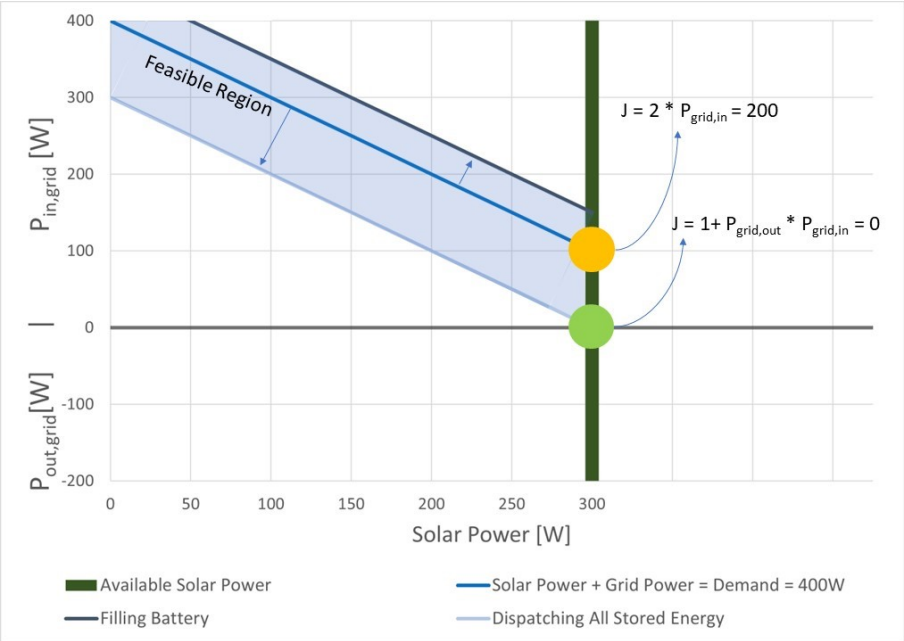


Figure 4.2: Decision space for a system with decision variables P_{grid}, $SolarPower$, $P_{battery}$ subject to: $SolarPower < 300W$; $SolarPower + P_{grid} + P_{battery} = 400W$;$(SoC-1)\cdot C_{nom} < P_{battery} < SoC\cdot C_{nom}$, with objective function (OF) as in 4.5, where x is set to 2. The optimum for the system without battery and the optimum of this system are shown. Again, the optimal lies in an intersection of constraints. Cable ampacity and conversion factors are ignored in this example.

common examples) as long term storage. The mismatch M, short-term storage demand S_{short} and long-term storage potential S_{long} can be defined respectively as follows:

$$M(t) = I_{solar}(t) – D(t) \tag{4.2}$$

$$S_{short}(t) = min(max(M(t),0), -min(M(t+12h),0)) \tag{4.3}$$

$$S_{long}(t) = max(M(t) - S_{short(t)},0) \tag{4.4}$$

where $I_{solar}(t)$ represents the solar PV generation at time t and $D(t)$ represents the energy demand at the same time t. Note that the short term storage demand calculation takes the *smallest* value between the surplus and the future shortage. Initially, it is reasonable to think that the *largest* value should be taken, to emphasize how much shortage needs to be covered, or how much surplus can be stored. The reason the smallest value is taken is to ensure that the short term storage demand represents the amount of mismatch that storage can reduce, *given the available energy generation.*

During the simulation process, several scenarios with short-term battery storage were run. Long-term storage potential was documented and presented as well. The round trip efficiencies used are elaborated on in Section 2.3.6.

4.2.3. MODEL WORKFLOW

With the input discussed in the previous two Chapters, the energy system model was built. A flowchart of the model is shown in Figure 4.3.

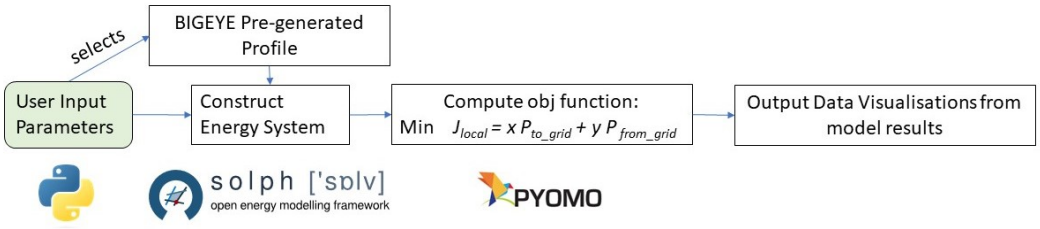


Figure 4.3: Simplified overview of the model workflow. This flowchart illustrates how the energy system model is generated based on user input. Solar PV profiles are generated using BIGEYE and the user inputs which of these generated profiles are to be input in the energy system as the main source besides the grid connection.

4.2.4. MODEL FORMALISATION

The execution of the model will be described here in words. First, the model is run from a main file that opens a Graphic User Interface (GUI) for the input parameters. This in turn stores the inputs into a dictionary and uses the dictionary to conduct the pre-processing calculations. The output variables of the pre-processing calculations are input into the OEMOF model, which determines the number of different components and properties based on the these output variables. The model is then run and solved in Pyomo, a Python-based, open-source optimization modeling language, that instructs a linear solver algorithm, in this case the GNU Linear Programming Kit (GLPK). The objective function is the same as in the above example:

$$\text{Minimize: } J = P_{in,grid} + P_{out,grid}, \tag{4.5}$$

Mismatch and power flow data are then stored and visualised accordingly. The directory structure of the code and the source code containing the central OEMOF model can be found in the Appendix (for the Appendix, refer to the digital edition). The order of execution of the code modules is also provided in the same Appendix.

4.2.5. ROBUSTNESS THROUGH STOCHASTICS

For system components that hold significant uncertainties, or those where the literature and field research pointed towards unpredictable behavior, some stochastics were introduced. This way, when the model is run several times, it will have a range of outcomes that represent the error in the outcome of the model. The stochastics introduced into the load are provided in Tables 2.4 and 2.5. Stochastics through varying weather data were not integrated in this study.

4.2.6. MODEL INPUT PARAMETERS

The input parameters of the model are those aspects of the farm that cannot be generalized due to their large influence on the demand pattern of the farm. It also includes the toggle of scenarios. Based on the findings in Chapter 2, the input parameters of the model are:

1. PV System Type (see 3.3.1 for clarification)
    - *Options*:
        - △ Vertical
        - △ Dome
        - △ Single-Axis Tracking
2. Scenario: Power Clipping (see 3.4.1 for clarification)

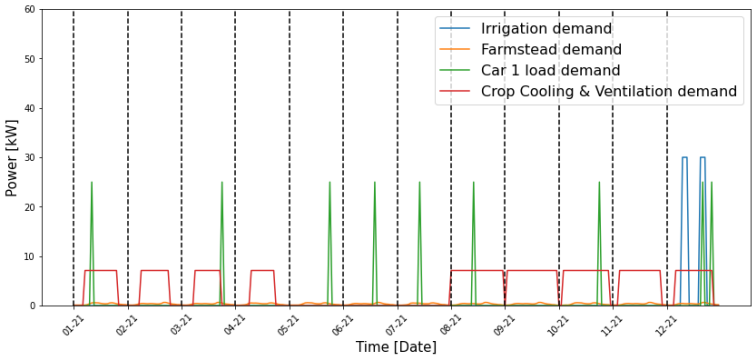
- *Range*: 100-40% of Wp

3. Scenario: Battery
   - *Quantity* (battery size [kWh])
4. Scenario: Electrification
   - *Options*:
     - △ Electric Loads
       - Include diesel loads as electric loads
     - △ Traditional Loads
       - Only state-of-the-art electric loads
5. Farm Type:
   - *Options*:
     - △ Open-Field
       - Crops:
         - Crop type
           - *Options*:
             - △ 30 most commonly tilled crops in The Netherlands
         - Area
           - *Quantity* [ha]
         - Last Month of Crop Storage
           - *Options*:
             - △ Months of the year
       - Tillage activities:
         - Weeks of Operation
           - *Range*: 1-52
         - Tillage Depth
           - *Quantity* [ha]
     - △ Dairy
       - Number of Cows
         - *Quantity*
       - Milking System Profile
         - *Options:*
           - Manual load
           - Automated load

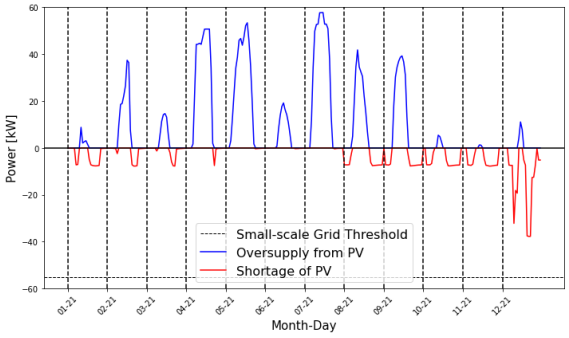
4.3. SIMULATION RESULTS

This Section provides a step-by-step, in-depth analysis of agricultural energy system simulations. In previous Sections, it was described how the building blocks for an energy mismatch model were developed and integrated. Using simulations generated by the model, this Section poses to answer the final research questions of this study, which were discussed in the introduction (Section 4.1). The questions concern the mismatch profiles on farms in different energy system scenarios and the applicability of these scenarios, given the local grid infrastructure. This entails that farms do not have to be *completely self-sufficient*, due to the presence of a grid connection, but it is critical that the allowed current through the grid connection is not exceeded. In Section 3.4.1, the limit of the grid connection for most farms, 55 kW, has been elaborated on. And since 36,000 of the 50,600 existing Dutch farms are smaller than 40 hectares, it is assumed that the small-scale grid limit is a representative limit for the feasibility of current grid infrastructure to facilitate a farm's energy system [14].

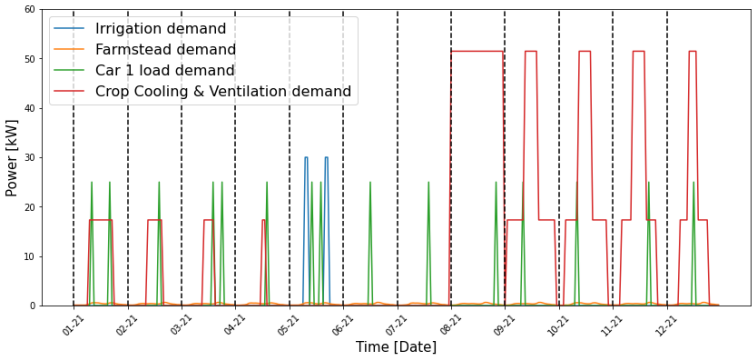
4.4. SIMULATION RESULTS OPEN-FIELD FARMS



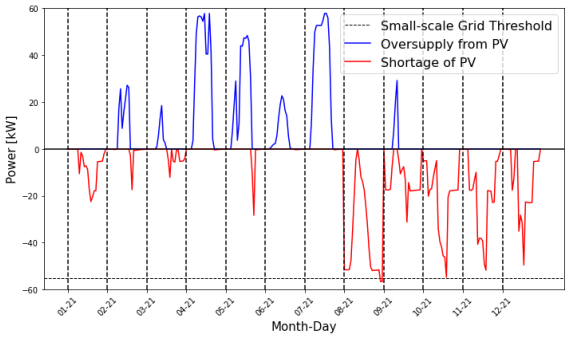
(a) Hourly demand for winter wheat farming throughout the year, mainly from ventilation during crop storage until March, irrigation after sowing green manure in late Summer and wheat in late fall, and charging electric cars.



(b) The mismatch profile for an average-sized winter wheat farm illustrates the misalignment of night-time ventilation and day-time PV yield. The PV system is sized so that 70% of its peak power is equal to the maximum allowed grid power.

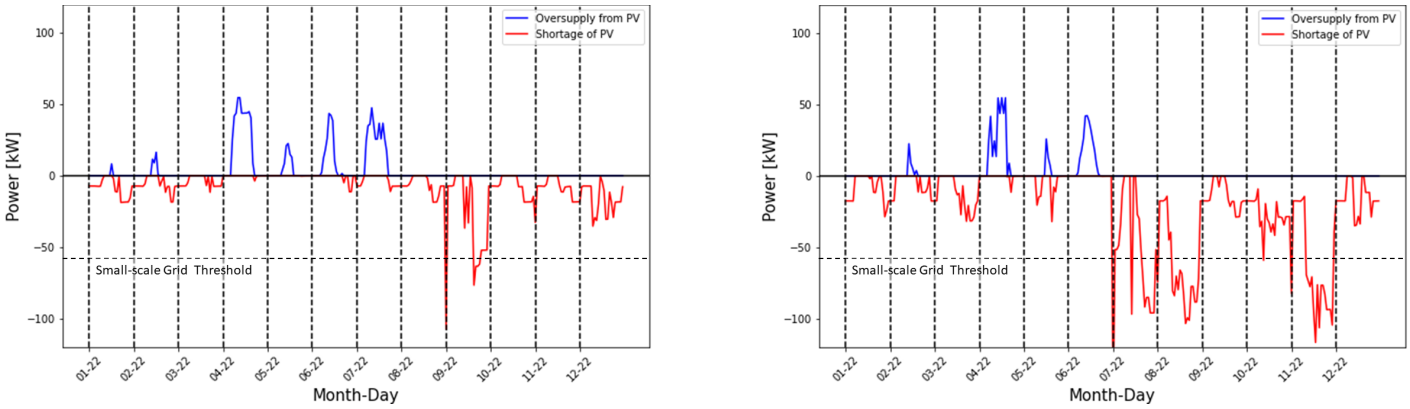


(c) Hourly demand for potato farming throughout the year. From January to March, there is still some crop storage left. In May and June, electricity is consumed for irrigation and from August onwards, the crop storage commences.



(d) For potato farming, the shortages are of a larger magnitude than wheat farming, despite being significantly smaller. The PV system is sized so that 70% of its peak power is equal to the maximum allowed grid power.

Figure 4.4: Profiles for state-of-the-art energy demand on a 43ha winter wheat farm (Dutch average) in 4.4a and corresponding mismatch in 4.4b. Idem dito for 30ha potato farming in 4.4c and 4.12d. The potato farm was scaled down to represent a farm with a small-scale grid connection. It is assumed that the timing of harvesting and sowing is the same each year.



(a) Mismatch for each 22nd day of the month for winter wheat farming practices.

(b) Mismatch for each 22nd day of the month for potato farming practices

Figure 4.5: Mismatch on the model farms, when all vehicles have been electrified.

4.4.1. STATE-OF-THE-ART ENERGY CONSUMPTION

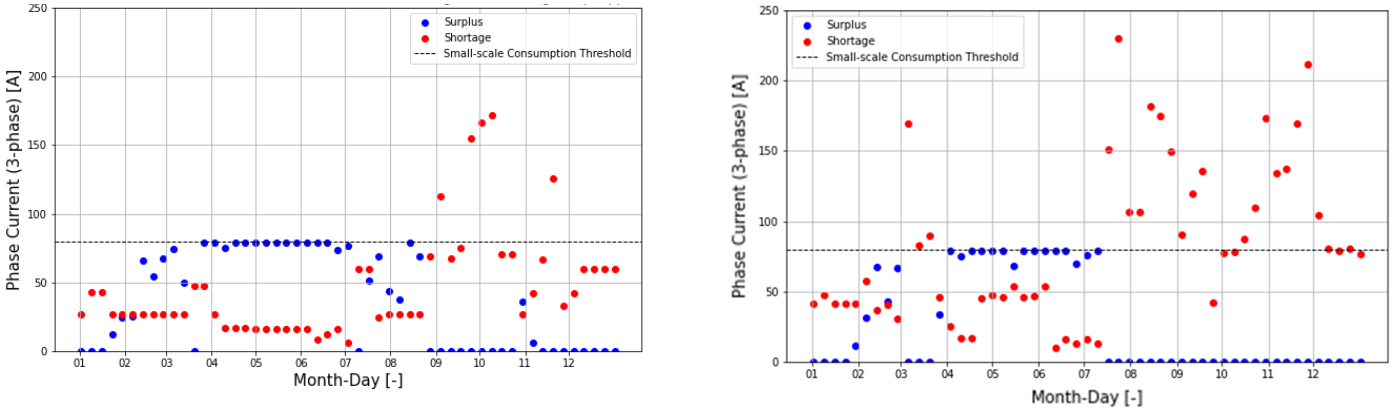
In this section, a scenario will be studied whereby a mid-sized open-field farmer has installed the largest possible PV system for a small-scale grid user. For open-field farming, the demand profiles for the cultivation of two crops on a state-of-the-art farm model are selected to illustrate the differences in possible outcomes as a results of varying sowing/harvesting seasons and crop storage needs. The two chosen crops are: winter wheat on sandy soil and potatoes on clayey soil. For these crops, the demand profiles and corresponding mismatch profiles are provided in Figure 4.4, in the case of an SAT PV system. Figures 4.4a and 4.4c distinguish the different loads for each system. Regular spikes in demand are from electric car use. The barn movers, also frequently used EVs, are not electrified in this scenario, since it is assumed that not many farms have more than one electrified vehicle, be it a car or a barn mover. Irrigation is assumed to be electric (the business case for it has been tried and tested [55]) and is done after sowing both the crop itself and green manure crop (for potatoes in May, June and September and for wheat in May, June and December). Baseload consumption from July to March comes from gradually decreasing ventilation and cooling for crop storage, which is an order of magnitude higher for potatoes.

In Figures 4.12d and 4.4b, the mismatch profiles corresponding to each system are shown. In both systems, the first three months are offset downwards with regards to the three months that follow, due to storage needs. These are mismatched with solar PV, since ventilation happens at night and the Sun is in the sky during the day. Irrigation is avoided in the hours with the highest Sun elevation to prevent leaf burn in plants, but this leads to a stronger mismatch with solar PV. For potato farming, the cooling demand coincides with solar PV profiles, as can be seen clearly in July. However, either on summer days with low solar insolation or on typical days in fall and winter, high shortages are present from the perpetuating crop storage demand.

Comparing these crops shows how different energy needs can be between open-field farming practices. Potatoes have very high consumption for both cooling and ventilation (remembering that this farm is smaller than the winter wheat case), whereas wheat only needs to be ventilated and for a shorter period.

4.4.2. ELECTRIFICATION

How does the situation change when the farm fully electrifies? As discussed in Section 2.3.6, this means all tractors for field operations run on batteries that are assumed to be switched out effectively and the batteries not in operation are charged during operation. The barn movers are also electrified, but these can only be charged outside of operation.



(a) Maximum current values in each week for 43 ha winter wheat farm.

(b) Maximum current values in each week for 30 ha potato farm.

Figure 4.6: Maximum current values each week on the model farms where all loads have been electrified.

Because the number of loads has increased significantly, it is no longer instructive to look at separated load profiles [1]. In Figure 4.5, the mismatch profiles for the electrified scenario are provided. The PV data has been kept the same. It can be observed that the mismatch profiles become more 'jagged', due to the regular but short charging of electric barn movers. The advantage of these new loads is that charging is more flexible. The solar PV peaks are therefore being used as suitable moments for charging the vehicles. It can be seen that where there used to be peaks in the first three months in Figure 4.4b, the mismatch is close to zero. Another observation is that where winter wheat has a seasonal mismatch, with similar degrees of surplus in summer and shortage in winter, the potato farm's mismatch profile consists largely of shortage. This demonstrates how challenging it will be to electrify certain farm types.

Both farms now exceed the small-scale grid connection. This means that both farms, whether it is well within the margin of its electricity consumption as with winter wheat, as, more trivially, the farms that have electricity consumption close to the maximum allowed current through their connection, are limited in their electrification efforts. In the next sections, scenarios will be discussed to extend these limits.

THE GRID AS LIMIT

So far, the profiles of the demand and mismatch have been provided to understand the power balance of an agricultural energy system on an hourly basis. However, to understand better how feasible it is for a farm to electrify, given the physical limit of available grid infrastructure, the analysis can be distilled by focusing on *the maximum current exchanged with the grid.* Remember that the maximum allowed current for most farms is 80A (from Equation 3.4). As long as demanded power on farms cannot be limited to this threshold, it will be challenging to make electrification possible. Figure 4.6 provides the maximum current values for each week of a year on the model farms. The red surplus values indicate power injected into the grid and blue shortage values represent the PV system's shortcomings in supplying the demand. Since the PV system is topped off at the maximum current, the surplus values never exceed 80A.

From Figure 4.6, shortages exceeding the grid limit are an exception for winter wheat, but a common occurence for potato farming. These occurrence are most common during the crop storage period, illustrating the high, seasonally misaligned demand of this activity. Interesting to note is that the surplus values are often zero in both cases. This means that when any solar PV power was generated in those weeks, it was used completely.

[1] For a better understanding of the separate loads, see Section 2.4

4.4.3. INFLUENCE OF PV SYSTEMS VS CROP SELECTION

To more broadly understand how the choice of PV system and that of selecting crops influence a suitable agrivoltaics match, a second metric is included complementarily to the maximum grid current discussed in the previous section. This second metric is the percentage of total consumption that is being supplied by on-farm PV generation throughout the year. Where the maximum grid current describes extremities, the overall self-sufficiency indicates the overall balance of the system. In Figure 4.15, the values for these two metrics are shown for combinations of five types of crops and the three PV system benchmarks. For comparison, all farm sizes are kept the same, at 43ha. The five crops are selected for their variety in sowing & harvesting periods, conventional soil types and crop storage needs. They are chosen from the thirty most commonly tilled crops in The Netherlands [35].

In this Figure, the sensitivities of PV system choice and crop choices can be compared. The influence of the type of PV system varies between crops. For winter wheat, the maximum current is less sensitive to the type of PV system than for broad beans. The wide range of maximum current values indicates the potential of demand side management. This is because the randomness of the model is in the demand. Therefore, when the demand aligns with PV generation due to this randomness, it will lead to a lower maximum current.

The influence of the PV system choice on the total rate of self-sufficiency is limited to several percentages (the highest being 7% for potatoes). Within this limited influence, the SAT system provides the highest rate of self-sufficiency in all cases. Winter wheat and broad beans are examples of crops that require field work in summer and have smaller (or none for broad beans) energy demand for crop storage. Cultivating these crops can therefore lead to a more balanced energy system.

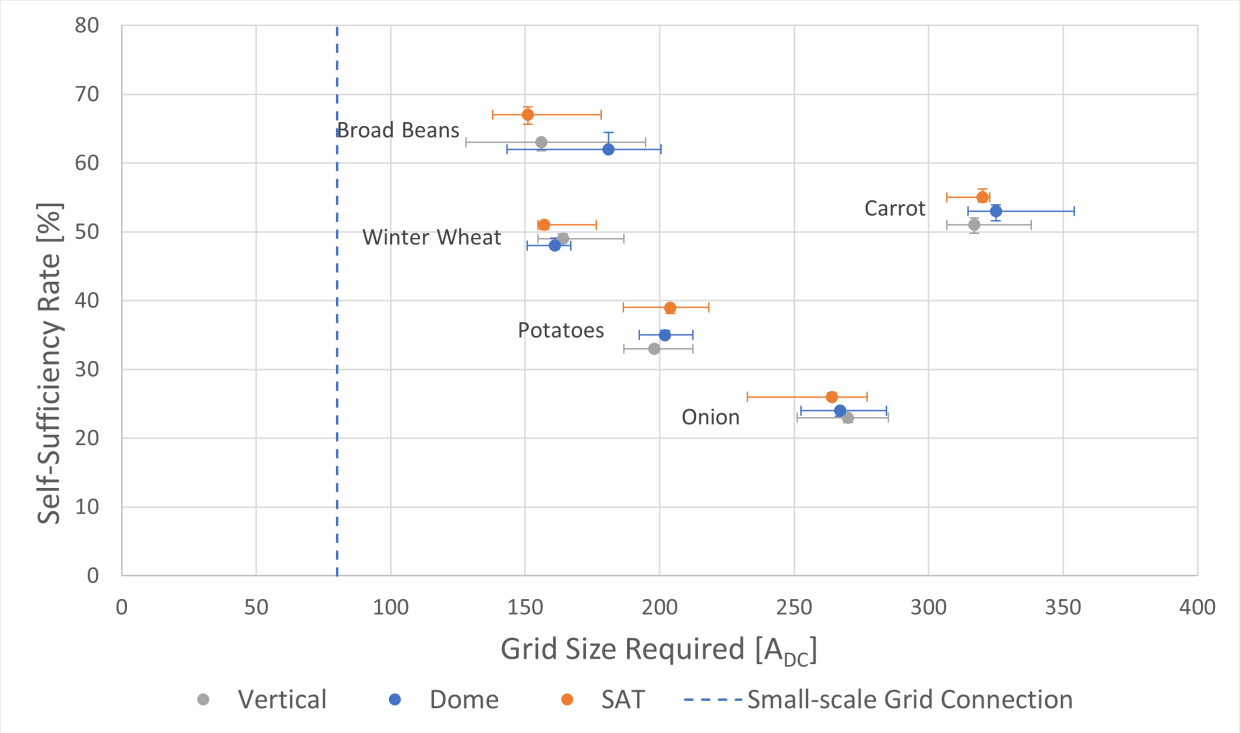


Figure 4.7: Self-sufficiency rate, which is the percentage of total demand that has been supplied by PV, against the required grid size for different crop and PV system combinations. A 43ha farm is considered. Each combination was run 10 times. Out of the 10 simulations, the error bars provide the maximum and minimum values. A self-sufficient farm would have a high self-sufficiency and low grid size.

4.4.4. SCENARIO SIMULATION

In this section, an overview for all combinations is provided for the effect of adapting the energy system on the self-sufficiency and required grid capacity. In the next section, the most significantly affected combinations are studied in more detail, while also studying the potential for using storage technology.

In all cases, the current threshold for small-scale grid use was crossed. However, the significant variations in both metrics in Figure 4.15 invite the consideration of measures that could further balance the system. In this Section, the results of simulations for systems with different technological features are discussed.

LOAD SHIFTING

Above, the potential of demand side management was eluded to. Thorough estimates of load flexibility was beyond the scope of this study. Especially for field operations, if these activities turn out to have flexibility, it could significantly impact self-sufficiency of the farm.

For the following two loads, there seems to be little reason why they could not be aligned better with PV yield profiles: ventilation, which can be moved to the daytime and irrigation, which can be moved to the noon hours. Analogous to the results in Figure 4.15, simulations were run with the two shifted loads. The results are provided in Figure 4.8. The impact of this scenario are varying for different crops.

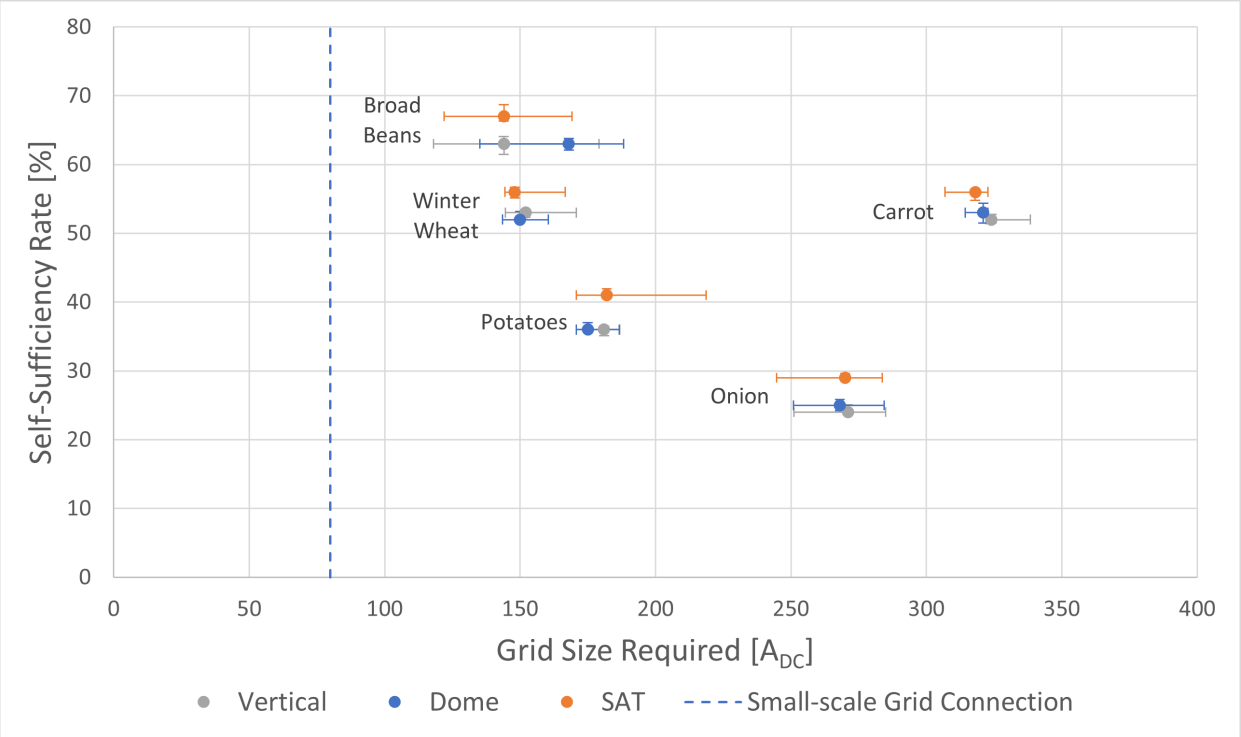


Figure 4.8: Self-sufficiency rate against the required grid size for different crop and PV system combinations, where loads have been shifted to align with hours with typically high solar insolation. A 43ha farm is considered. Each combination was run 10 times. Out of the 10 simulations, the error bars provide the maximum and minimum values.

As expected, due to their lack of ventilation demand, broad beans and carrot are not significantly impacted by this scenario, with the exception of broad beans' reduction in maximum current, implying that irrigation played a role in the high currents. For all crops with ventilation, a significant reduction in maximum current and increase in self-sufficiency can be seen. This reduction is visualised more clearly in Figure 4.10

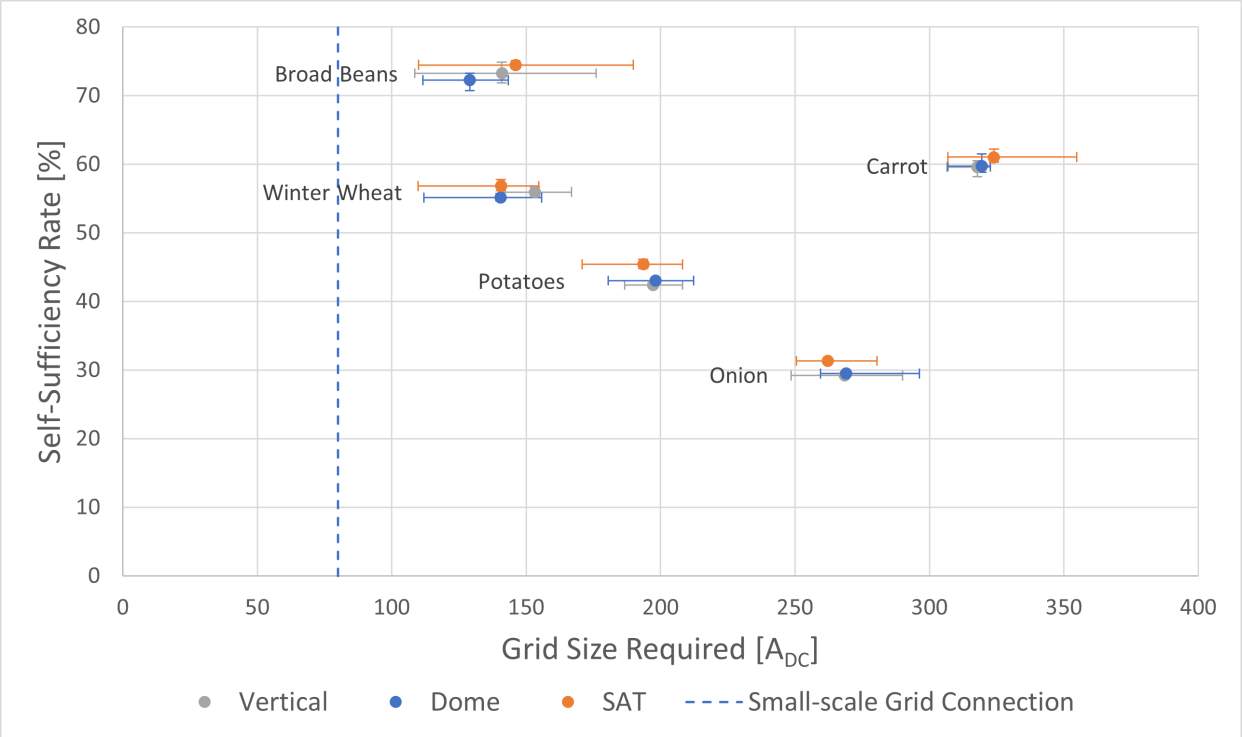


Figure 4.9: Self-sufficiency rate against the required grid size for different crop and PV system combinations, where the PV was topped off at 40% of STC peak power and sized so this 40% is equal to the small-scale current threshold. A 43ha farm is considered. Each combination was run 10 times. Out of the 10 simulations, the error bars provide the maximum and minimum values.

CLIPPING POWER

In Section 3.4.1, the potential of oversizing the installed PV peakpower was eluded to. From economic studies, it was shown that clipping power up to roughly 40% is considered to make economic sense, depending on the context. Therefore, a scenario is simulated where the PV system is oversized and clipped so that up to 40% of its peak power can be exchanged with the grid. This means that the installed peak power is increased, so that 40% of this peak power is equal to the small-scale grid threshold. This results in an increase of the energy yield equal to the increase in specific yield (see Table 3.2). Note that in the previous scenarios, the clipping factor was already set to 70% since this is standard for most Dutch ground-mounted solar projects (see Section 3.4.1). The values for the maximum currents and the self-sufficiency for this scenario are shown in Figure 4.9.

For every crop choice, the influence of clipping power on the self-sufficiency is significant, with up to 10% increase for potatoes in combination with vertical. The averages of maximum currents also decreases in this scenario. The fact that the ranges are sometimes higher for this scenarios, is more likely to be a symptom of the statistical shortcomings of 10 simulations per combination than a feature to compare the scenarios with.

4.4.5. THE POTENTIAL OF STORAGE TECHNOLOGY

In this section, the two cases affected most significantly by the scenarios from the previous section (broad beans and winter wheat) will be studied in more detail. Additionally, the potential contribution of short term systems, in the form of Li-ion batteries and long term storage systems, in the form of hydrogen conversion and storage, will be indicated.

SHORT TERM STORAGE

In Figure 4.10, the effect of the scenarios on the self-sufficiency of two systems is shown.
Since broad beans has no crop storage needs, it was not affected by ventilation load shifting. Since the irrigation was also shifted, this means that only the shifting of the ventilation load had a significant effect on the mismatch. The clipped power had a similar effect of about 7% on the self-sufficiency of the system.

To study the influence of short term storage, two different battery sizes were then introduced. Implementing a 30 kWh battery into the model increases the self-sufficiency by 8 % for the broad beans and 6 % in the case of winter wheat. Simulations with larger batteries were run, and the increase in size had a regressive effect on the self-sufficiency. The largest size simulated, 130 kWh, was based on the hypothetical situation in which a farmer uses two old tractor batteries for a stationary battery system. These two batteries are decommissioned after the initial capacity of 80 kWh has decreased to 65 kWh. From these simulations, it was observed that the larger the battery, the less significant the increase in self-sufficiency, as can be seen for the impact of implementing a 130 kWh battery.

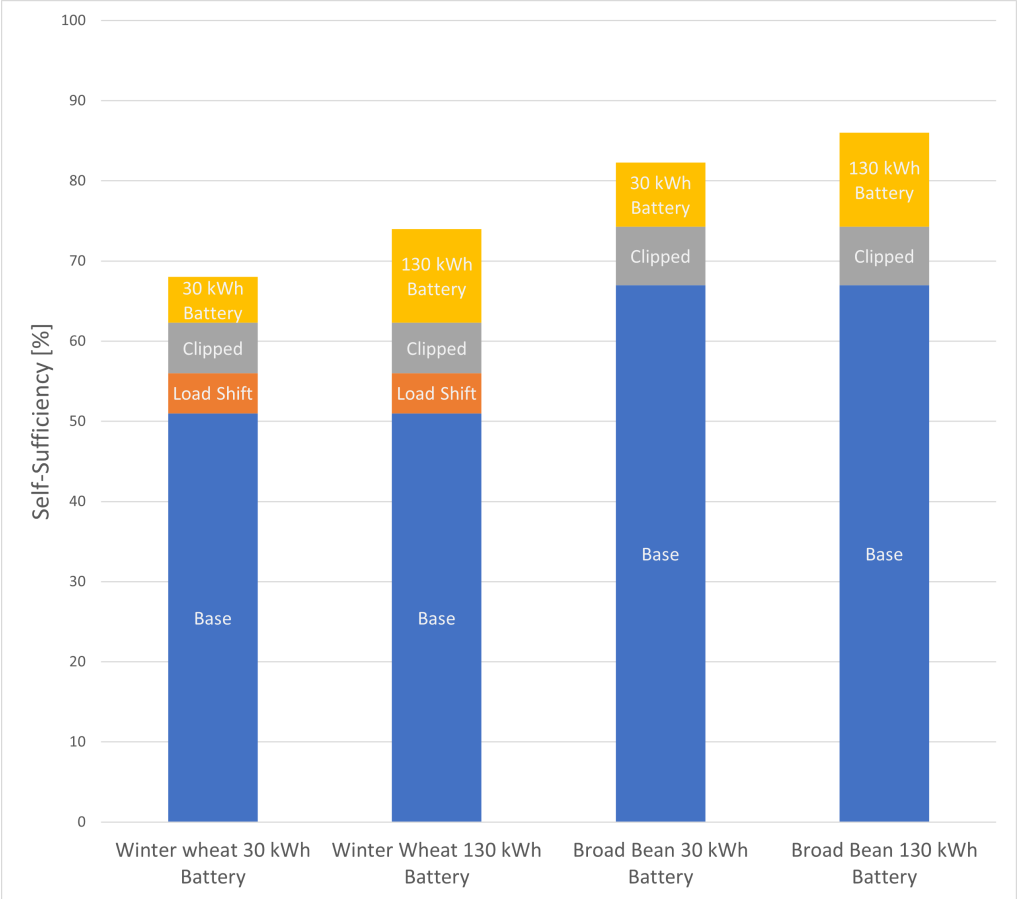


Figure 4.10: The effect of the different scenarios on the self-sufficiency of the two most balanced crop-PV combinations. In both cases, an SAT system was used. The combination of different scenarios is approximately equal to the sum of the parts.

LONG TERM STORAGE

The reason the maximum current metric is not included in Figure 4.10, is because the batteries had no noticeable effect on it. This is because the high power demand of tillage activities cannot be dampened by the scenarios discussed so far. In Figure 4.11, an example is shown of a farm that grows

	Broad Beans	Winter Wheat	Potato	Carrot	Onion
Total Annual Shortage (MWh)	0.42	0.91	4.46	9.03	11.8
Potential Electricity from Hydrogen (MWh)	17.5	18.25	9.80	18.08	5.99

Table 4.1: These two metrics serve as indicators of imbalance of the system and the degree to which they can balance one another. The potential electricity from hydrogen is equal to the surplus after short term storage balancing and represents useable electrical energy after well-to-wheel conversion of 0.28.

winter wheat and has implemented all the scenarios in Figure 4.10, with the exception of having a 30 kWh battery, not 130 kWh. It can be seen that the shortages are generally low and the surpluses high, but the spikes in October remain from the ploughing activities. Therefore, a final look into the

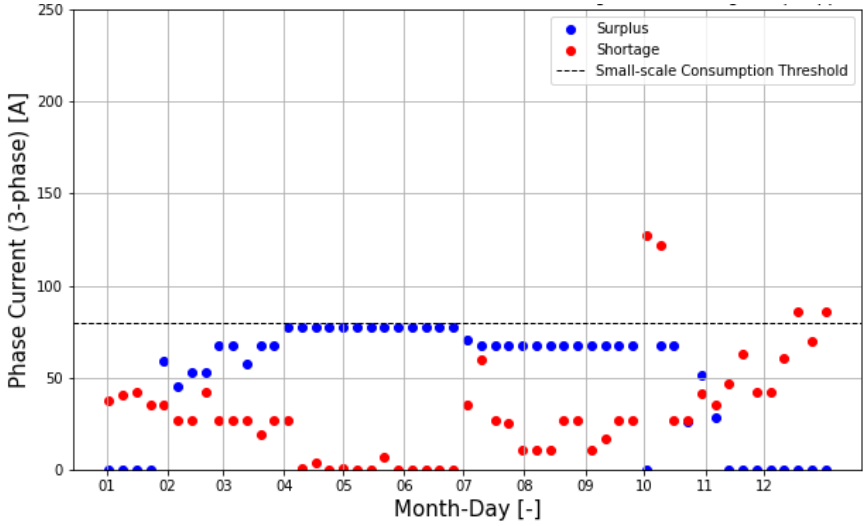
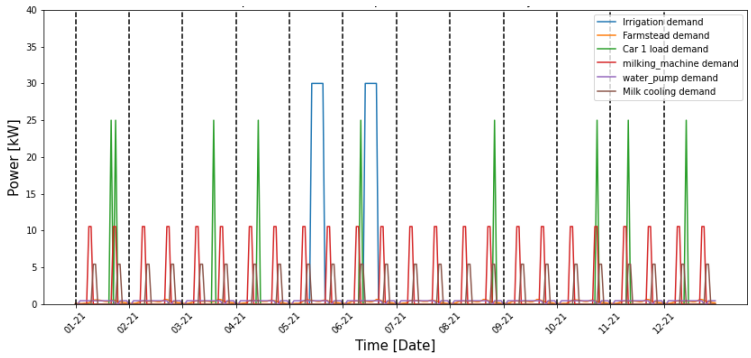


Figure 4.11: Despite the low shortages throughout the year, the spikes from coinciding of high-power activity (tillage and storage activities) cannot be dampened in the scenarios in Figure 4.10.

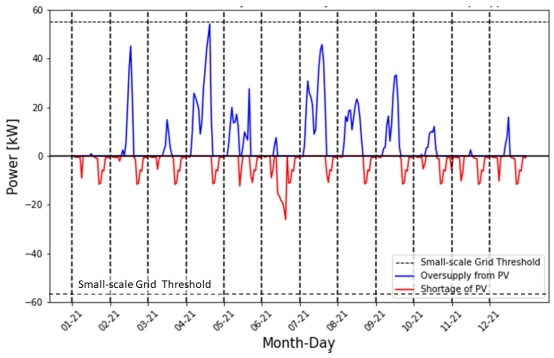
potential hydrogen production is taken. In Table 4.1, the total annual shortage is compared to the potential electricity yield from long-term hydrogen storage, calculated using Equation 4.2 with a conversion factor from generation to tractor drawbar power of 0.28. This well-to-wheel efficiency (see Section 2.3.6) is taken on the assumption that the most concentrated shortages are due to tractor operations, which are assumed in this case to be supplied using hydrogen fuel cells (see Section 2.3.6).

The balance between seasonal storage from surplus and the total annual shortage varies with several orders of magnitude depending on the situation. In the broad beans and winter wheat cases the shortages have been almost completely neutralized, as discussed in previous sections and illustrated in Figure 4.11. For potato and carrot, the total annual shortage and electricity surplus from hydrogen storage is more balanced. Future work is needed to validate the technical and economic feasibility of using hydrogen to balance energy systems on farms with these types of crop storage needs and tillage activities. With this overview, a ball-park estimation is provided of the scale of shortage and surplus for these systems.

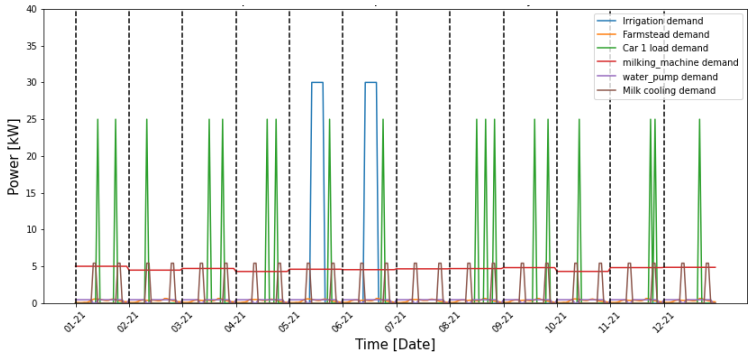
4.5. SIMULATION RESULTS DAIRY FARMS



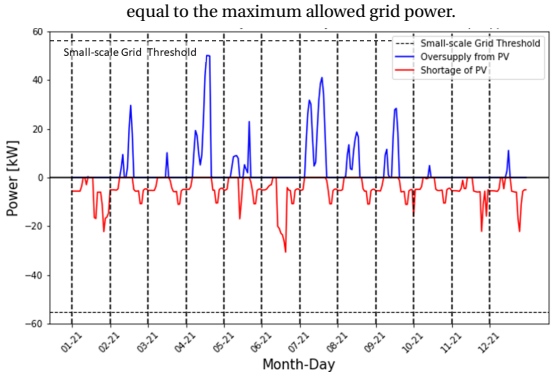
(a) Hourly demand for dairy farming with manual milking throughout the year.



(b) The mismatch profile for an average-sized dairy farm with a manual milking parlor illustrates . The vertical PV system is sized so that 70% of its peak power is equal to the maximum allowed grid power.



(c) Hourly demand for dairy farming using automated milking systeem throughout the year.



(d) For dairy farm with automated milking system, . The PV system is sized so that 70% of its peak power is equal to the maximum allowed grid power.

Figure 4.12: Profiles for state-of-the-art energy demand on 43ha dairy farms. For an easy comparison with open-field farming, the same size farm was chosen, despite Dutch average dairy farm size being 43ha. The chosen PV system was a vertical system, capped at 70% of module STC and coinciding with the maximum allowed current for small-scale grid connections.

Analogous to the previous section, simulating energy systems for state-of-the-art dairy farms will be reported on, followed by electrification and some scenarios, including the potential for storage technology.

In Figure 4.12, the load profiles and mismatch profile for a dairy farm of equal size to the farms in previous sections are provided. The load sizing is approximately equal to winter wheat farming of the same size, where milking operations and ventilation demand approximately 10 kW. Both systems use exactly the same PV profile, for comparison. The difference between the two cases is the use of a manual milking system versus an automated milking system. The car loads are modeled the same, but the varying number of trips demonstrates the randomness included in the model. The manual milking is done early in the morning and later afternoon. It can be seen in the mismatch profile that the late afternoon peaks are not aligned with the vertical PV yield profile, whereas the morning milking is more commonly supplied by solar power. The dual peak profile for vertical is therefore closer apart than the timing of milking, which is around 12 hours apart. For the automated system, the daytime load is supplied on most days with PV, but in the nighttime, the system continues to demand power and cannot be supplied by solar power. Therefore, both systems have some degree of misalignment with PV, with the noteworthy difference that automated systems can demand up to several multitudes more energy than a manual milking parlor. The irrigation occur during the start of the mowing season, in May.

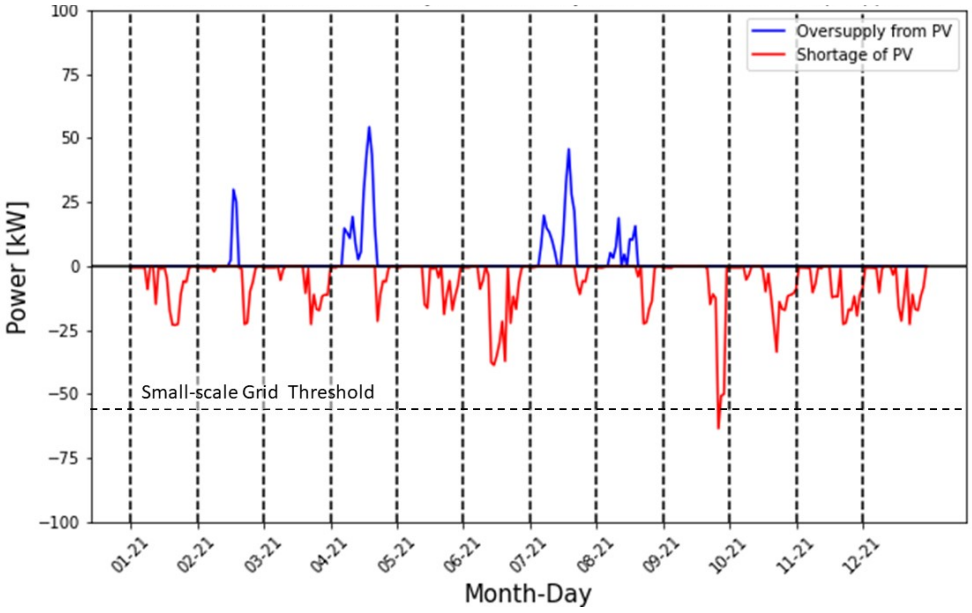


Figure 4.13: Mismatch for a farm with a manual milking system.

Overall, compared to open-field farms with the same size, the peaks in energy demand are significantly lower. This can be attributed to the fact that there are no seasonal differences in load profiles for state-of-the-art Dutch dairy farms.

4.5.1. ELECTRIFICATION

How does the situation change when tractors are electrified? From Section 2.3.3, it should be evident that tractors are the dominant energy consuming tools on a farm, especially for open-field and to a lesser degree for dairy farming. For dairy farming, field operations are the only strongly seasonally fluctuating activities, and patterns vary depending on farming preferences. In Figure 4.12, it is illustrated that the difference in mismatch profiles between manual and automated systems is not significant enough, relative to the power demand from field operations and barn movers. Only the manual case will therefore be considered.

In Figure 4.13, the mismatch profiles for dairy farms with electric tractors and barn movers are shown. Throughout each day of the year, the surpluses are replaced with local shortage peaks from the electrified barn mover and feeding tractor. Despite the fixed feeding moments in the morning, the reason there are no consistent shortage peaks at that time can be attributed to the flexibility that charging an electric vehicle with known load patterns enables. In other words, if a vehicle is used at specific moments, there is no urgency to charge it and it can simply charge when there is solar PV.

THE GRID AS LIMIT

Can small-scale dairy farmers keep farming when they electrify, while using low current grid infrastructure? In Figure 4.13, it could already be seen that on a day where the tractor mows the grass all day, like in September, the power demand peaks to values several times higher than more typical days. This has a detrimental effect on the optimal use of grid capacity, if the grid were to be sized for these peaks.

As in Section 4.4.2, to gain a better understanding of the frequency and intensity of these peaks, Figure 4.14 provides an overview of the highest currents each week that are demanded of and supplied to the grid for dairy farms with the two types of milking systems. Due to the field operations in the summer, there are weeks with power demands higher than the maximum PV generation. Without energy storage, demand side management or other strategies, these peaks will dictate the required grid

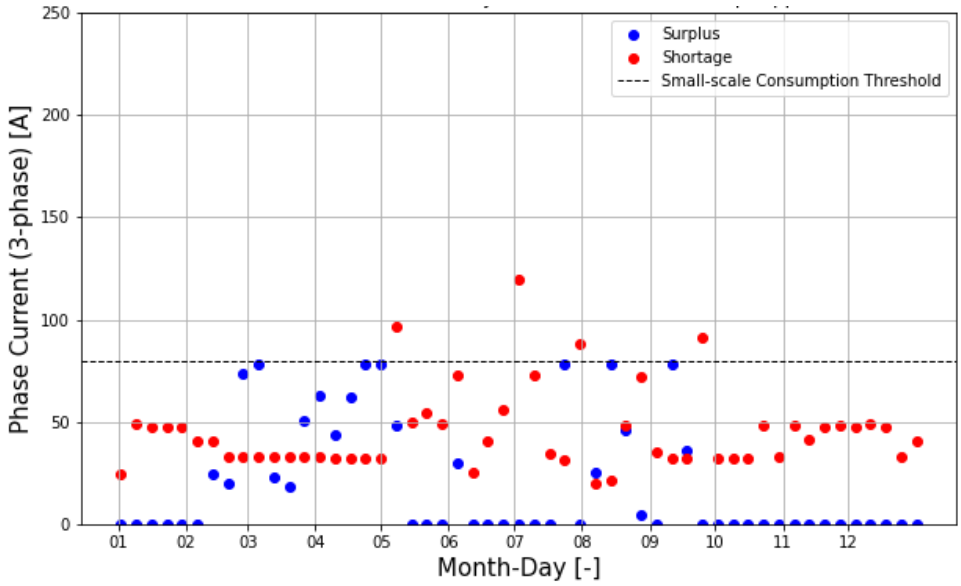


Figure 4.14: Weekly highest current demanded from the grid for a dairy farm with all-electric loads.

capacity and lead to inefficient grid use.

Similarly to open-field, there are many weeks where no current is supplied from PV to the grid. This indicates that the battery charging of electric vehicles leads to intelligent use of PV power, or that there is so much electricity demand that all PV is consumed directly.

4.5.2. SCENARIO SIMULATION & INFLUENCE OF PV SYSTEM

In this section, the scenarios from Section 4.4.4 that are applicable to dairy farming will be compared. This section combines the last three sections of open-field farming, since for dairy, there is only one farm archetype, as opposed to the studied crop cultivations in open-field. Again, the *self-sufficiency rate* of the farm will be set against the required grid size, as determined by the highest power demands at any time. As mentioned in the previous section, automation will no longer be considered in the comparison, due to the marginal difference in overall power demand and its higher energy demand compared to manual milking. The fluctuations in required grid size are greater than the differences between scenarios and are more significant for the dairy model than open-field. It is therefore important to remain critical towards these outcomes. Nevertheless, the averages vary per scenario and are inversely proportional to the self-sufficiency rates. What also remains consistent throughout is that vertical systems require higher grid size. Further study of the data, by for example looking at the self-sufficiency rate, shows that this has little to do with the overall mismatch of a system with vertical PV, but more with the rare occasions when loads are aligned in the model. These peak moments are often around noon, when vertical has low yield. Each scenario leads to an increase in self-sufficiency, with the most significant difference when being the addition of a 30 kWh battery (±8%). This shows, similarly to open-field, that the first residential-sized battery has a stronger balancing effect per kWh compared to larger batteries.

LONG TERM STORAGE

It is clear that agricultural energy systems supplied mainly by solar are not inherently suitable for complete self-sufficiency. As we have seen in Section 1, however, reaching an yield of annual solar PV as high as the farm's energy demand can be achieved without compromising significant agricultural activity. Therefore, in Table 4.2, a ball-park sizing of the electricity that can be made available year-round using hydrogen as long-term storage is shown. With the PV systems used in this chapter, and correcting with a conversion factor of 0.28 (see Section 2.3.6), the amount of electric energy is

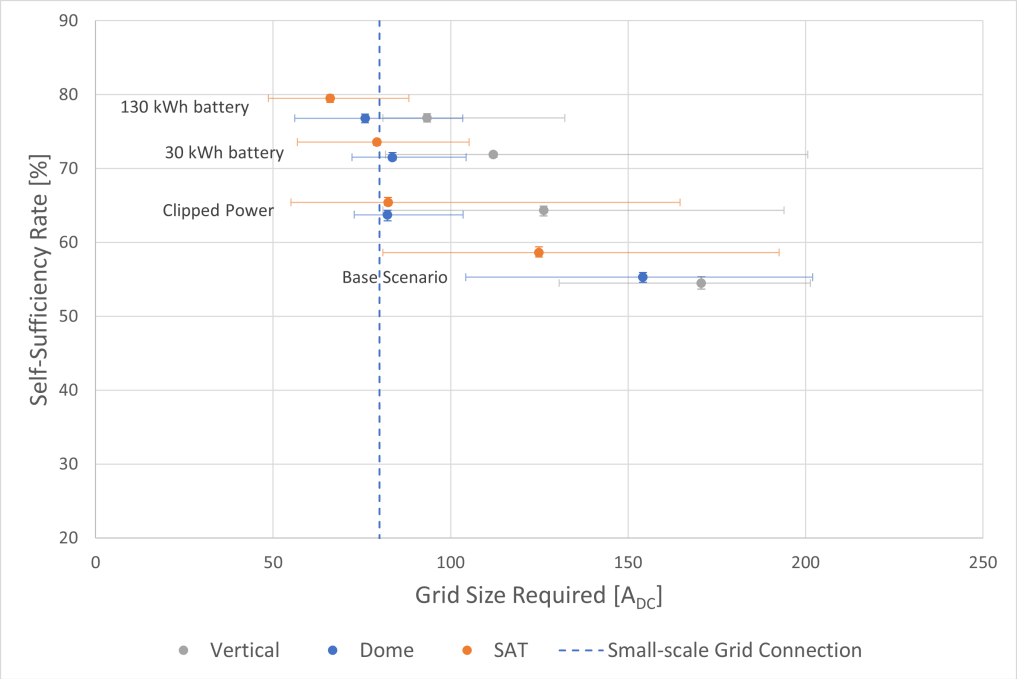


Figure 4.15: Percentage of the total demand that has been supplied by PV against the required grid size for all scenarios and different PV system combinations. A 43ha farm is considered. Each combination was run 10 times. Out of the 10 simulations, the error bars provide the maximum and minimum values. A self-sufficient farm would have a high self-sufficiency and low required grid size.

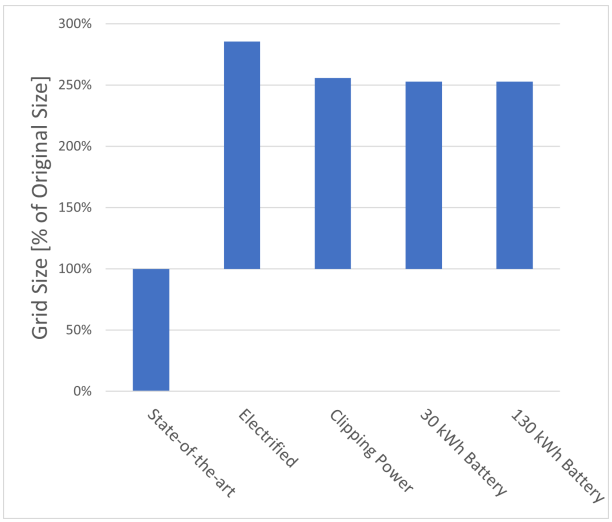
	Dairy SAT PV	Dairy Vertical PV
Total Annual Shortage (MWh)	0.63	0.71
Potential Electricity from Hydrogen (MWh)	12.7	7.92

Table 4.2: These two metrics serve as indicators of imbalance of the system and the degree to which they can balance one another. The potential electricity from hydrogen is equal to the surplus after short term storage balancing and represents useable electrical energy after well-to-wheel conversion of 0.28. This factor is used because it assumes that the most concentrated shortages are due to tractor operations, which are assumed to be supplied using hydrogen fuel cells (see Section 2.3.6). The two PV system extremes for hydrogen production are shown, to indicate the significance of choosing the PV system.

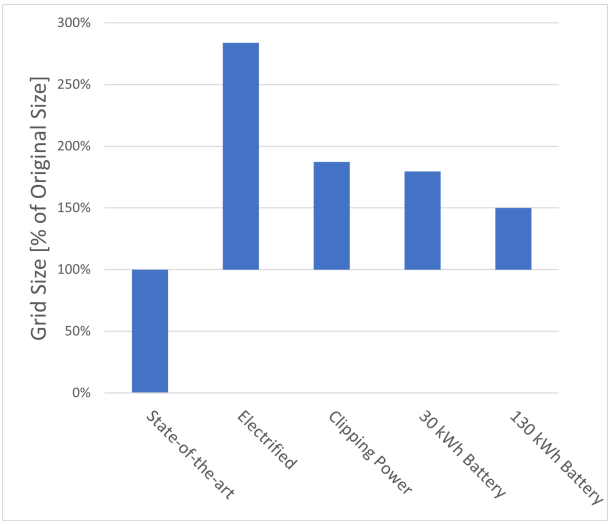
11-20 times the annual shortage left to balance. Scenarios can be imagined where a farmer can provide this energy to provide energy for other farms to balance their mismatch. Considering the severity of seasonal mismatch and high power demands for field oeprations using tractors, and considering that clipping power to lower AC costs is a real trend, producing hydrogen from clipped power to provide a supply for field operations belongs to the more realistic options for a renewable, self-sufficienct agricultural system.

4.6. RELIEVING STRAIN ON THE GRID

Ultimately, for decarbonizing Dutch agricultural energy systems, the degree of strain this transition puts on the grid is what determines its feasibility. And although it has been illustrated that self-sufficiency can be improved with certain technological implementations, a main hurdle remains: high demand peaks for which solar PV cannot guarantee supply. For a crop with a low grid size requirement: winter wheat (see Figure 4.15), the grid size requirements for different scenarios are shown in Figure 4.16. The maximum power demanded from state-of-the-art winter wheat and dairy farms are normalized for comparison. These two farm types of the same size initially have similar grid



(a) The increase in power demand from the grid for different scenarios, proportional to the original peak demand of a farm growing winter wheat.



(b) The increase in power demand from the grid for different scenarios, proportional to the original peak demand of a dairy farm.

Figure 4.16: The various scenarios and their effects on the required grid size for the energy system of a 4.16a) winter wheat and 4.16b) dairy farm with manual milking. The values are mean values from 10 simulations.

requirements: milking is about 10 kW, as is ventilation of wheat. It needs to be possible to charge a vehicle and run the lights during this time, and to irrigate. When the farm is electrified, the electric vehicles for field and barn operations cause significant power spikes. While the scenarios bring peaks in dairy farming down close to original grid capacity, the effect on the peak moments for winter wheat farming is minimal. This is a trend in other crop types as well. In most cases, this has to do with the coincidence of *inflexible* demands for open-field farming. For dairy farming, charging of barn movers and cars can be done flexibly because milking and field operations occur during short periods. This shows the model's ability to dispatch power flexibly. For crop storage and tillage operations in open-field farming, weeks of continuous power is demanded, so there are no opportunities for charging during low demand. Although this simulation is based on a list of assumptions with a strong need for validation, it does indicate the need for long-term storage options if the farm were to electrify without grid reinforcement.

4.7. CONCLUSION

Chapter 4 integrates the demand and generation profiles into an energy system model that optimizes self-sufficiency and grid management for farms. Through scenario analysis and technological interventions, the chapter demonstrates the model's capability to enhance energy efficiency and sustainability in agricultural settings.

5 | Implications

In this section, a step backwards is taken to discuss the implications of the findings of this study. This is done because the integration of renewable energy in agricultural practices holds profound implications that extend beyond the immediate benefits of reducing carbon emissions and enhancing energy security. This study underscores the transformative potential of such integration, urging a reevaluation of current energy systems, infrastructure, and the broader societal roles that accompany these changes.

5.1. Diversification of Power Sharing Systems

Addressing the mismatch between energy production and consumption is crucial for the viability of renewable energy in agriculture. This challenge can be turned into an opportunity by creating synergies with other types of prosumers, such as businesses and towns. These synergies can become known as 'energy communities' or 'energy hubs'. For instance, urban areas and industrial zones with consistent energy demands could absorb surplus energy generated by farms during peak production times. Conversely, energy generated by urban solar installations or industrial waste heat recovery systems could support farms during their peak demand periods.

Such collaborative energy networks necessitate advanced smart grid technologies capable of real-time energy management and distribution. These systems would not only balance supply and demand more effectively but also enhance grid stability and efficiency. Implementing these technologies requires significant investment and innovation, driving advancements in energy storage, grid management, and predictive analytics.

5.2. Techhnological Diversification

The successful electrification of agriculture hinges on the development and deployment of new technological infrastructure. Current grid capacities must be expanded and modernized to accommodate increased and fluctuating loads from renewable energy sources. Smart grid technologies, which enable dynamic energy management and facilitate the integration of diverse energy sources, are essential. These technologies can optimize energy flows, prevent overloads, and ensure reliable power supply even in the face of variable renewable energy production. Combining different renewable energy sources, such as solar, wind, and biogas, can also enhance energy reliability and sustainability. Hybrid systems that leverage the complementary nature of these sources can provide a more stable and continuous energy supply. For instance, wind energy can offset the lower production of solar PV systems during cloudy or nighttime conditions, while biogas can serve as a reliable backup during prolonged periods of low renewable generation. Testing this at scale but in experimental context will be valuable to widespread adoption. An example is the Switch Lab, an experimental setup for a diversified energy system, operated by TNO in collaboration with Wageningen University & Research.

5.3. Social Acceptance

Decarbonizing the agricultural sector requires farmers to shift from energy consumers to prosumers. This study has shown that energy self-sufficiency is limited, but that equipping farms with solar PV systems and other renewable energy technologies reduces their dependence on centralized power grids and fossil fuels. It raises the need for participation of a variety of consumer types, because matching localized supply and demand requires a case by case study. The roles of the energy value chain will shift drastically, starting the debate on the farmer's role in a new energy market. So far, the sector's stance in the energy transition is fragmented, but overall, lethargic. Involving farmers in transitioning to renewable energy systems will be characterized by political and cultural complexity.

5.4. POLICY AND ECONOMIC IMPLICATIONS

The broader implications of this transition also encompass policy and economic dimensions. Policymakers must create an enabling environment for the adoption of renewable energy technologies in agriculture. This includes offering financial incentives, subsidies, and supportive regulatory frameworks that lower the barriers to entry for farmers. This way, many key technologies such as electric tractors and long-term energy storage can benefit from a learning curve, similar to other renewable energy technologies from the past. Additionally, policies that facilitate the development of local energy exchange and peer-to-peer energy trading can enhance the economic viability of decentralized energy systems.

Economically, the shift towards renewable energy in agriculture can create new jobs and business opportunities in the green energy sector. Solutions are needed for efficient energy exchange, in the form of both electricity and molecules. A new form of contracting work is needed to facilitate decarbonization of field operations.

5.5. CONCLUSION

In summary, this study has shown the non-triviality of decarbonizing the agricultural energy system. New synergies between different types of prosumers and advancing smart grid technologies need to be found. This study not only highlights the potential for renewable energy in agriculture but also underscores the necessity in future work of holistic approaches that encompasses a combination of technological, societal, and policy dimensions.

6 | Conclusions and Recommendations

This study directly addressed the research questions regarding energy consumption, self-sufficiency, and grid capacity needs on dairy and open-field farms. It identified the primary activities that contribute significantly to electricity and diesel consumption. In dairy farming, energy demand is characterized by consistent daily profiles throughout the year, with activities such as milking and cooling being the major consumers. In contrast, open-field farming exhibits highly variable energy consumption, closely tied to crop needs, with activities like irrigation and harvesting displaying substantial seasonal and hourly variations. The predominance of diesel use, particularly for tractor operations in open-field farming, presents significant challenges for electrification.

To quantify energy self-sufficiency and power exchange with the grid, detailed modeling of hourly and seasonal energy demand was conducted. The results varied in confidence, particularly for field operations, where the diversity of practices introduces considerable complexity. This underscores the need for further empirical and statistical analyses to refine these models, especially as electrifying diesel-dependent activities would profoundly alter power demand profiles.

The study also examined the effects of fully electrifying farm loads on energy self-sufficiency and grid capacity requirements. Electrification is anticipated to significantly transform energy demand, particularly in open-field farming. While the models indicated that substantial levels of self-sufficiency could be achieved—75% for dairy farms and 82% for open-field farms—electrification could lead to pronounced seasonal peaks in energy demand, presenting new challenges for grid capacity, particularly during peak operations in open-field farms.

Furthermore, the study explored strategies to maximize self-sufficiency and minimize grid capacity needs through load shifting, power clipping, and energy storage. The findings suggest that power clipping and the implementation of residential-size batteries are the most effective strategies for reducing peaks in power mismatch and enhancing self-sufficiency. Although load shifting shows potential, it requires further validation due to the unpredictable nature of field operations. The study emphasizes the importance of demand flexibility and long-term storage solutions, such as hydrogen production from excess PV power, as essential for managing seasonal mismatches between energy generation and consumption. These applications deserve further research in case study settings, to validate technical feasibility, and in the context of systemic energy transition studies, to study its societal potential. Placing these technologies, but also the metrics of self-sufficiency, in the context of power sharing with other users and producers will progress towards a better understanding of the dynamic, decentralized agricultural energy system of the future.

In summary, while the electrification of farms using PV systems holds great promise, the path forward requires rigorous validation and comprehensive planning to overcome inherent challenges and uncertainties. The insights gained from this study provide a valuable foundation for future research and development efforts aimed at creating more sustainable and resilient agricultural practices.

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