

Modelling and Simulation of All-Electric Machines and Renewable Electric Power Systems in Agricultural Operations

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Abstract. Today's operation of agricultural machines is still characterised by the use of fossil fuels. In the future, all-electric agricultural machines can be used, whose energy requirements must be covered by local renewable energies or the power grid. The occurrence of limit value violations in the power grid can slow down and hinder this change in agricultural operations. For this reason, this paper describes the modelling and simulation of all-electric agricultural machines, renewable energy systems and rural power grids and the evaluation of suitable energy supply strategies for the machines and needed investments in the power grid.

Introduction

The restructuring of the German energy system in the context of the Energiewende requires the interaction and commitment of private and commercial stakeholders. As one of the main players in decentralized energy production, today's agriculture already has a special role in the Energiewende. In addition to the widespread photovoltaic plants, agriculturally operated biogas plants can be used to provide weather-independent electrical and thermal power. The combination of different generation and storage systems leads to a variety of energy structures with different technical and economic potential. In combination with new electricity applications in agriculture, such as all-electric agricultural machines, these energy structures have the potential to make agriculture sustainable in the long term. To determine the technical-economic potential

and to derive suitable recommendations for action for the involved stakeholders, it is necessary to carry out holistic modelling and simulation of the involved technologies. Therefore, this paper describes the modelling and simulation of agricultural influenced energy systems and power grids with a focus on all-electric agricultural machines. In a simulation of different scenarios, suitable energy supply strategies are derived.

1 All-electric Agricultural Machines

More and more manufacturers of agricultural machinery have turned their attention to all-electric agricultural machines in recent years. Given the further development of power electronics and electric motors, as well as new requirements in efficiency and environmental protection, a future use of all-electric agricultural machines is realistic and comprehensible. For many processes in field cultivation, there are currently only prototypes and concepts and no market-ready products, which is why the modelling approach of all-electric agricultural machines, as shown in Figure 1, is based on empirical values and consumption profiles of diesel-powered agricultural machines. The

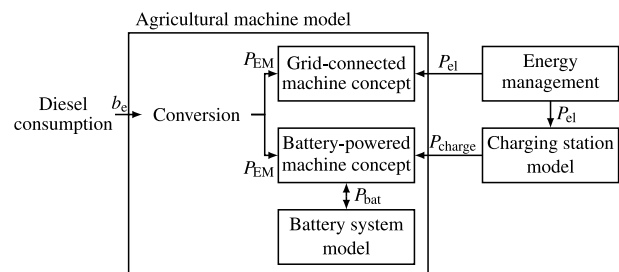


Figure 1: Modelling approach for the all-electric agricultural machines.

diesel consumption profiles b_e are converted to electrical power values P_{EM} , which represent the power requirement of the electric drive train. These electrical consumption profiles serve as input data for the two modelled machine concepts: the battery-powered agricultural machine and the grid-connected agricultural machine. The battery-powered agricultural machine is recharged by the charging station with the charging power P_{charge} . The charging station as well as the grid-connected agricultural machine are connected to the energy management system via their electrical power consumption P_{el} . The conversion process as well as both machine concepts are explained in more detail below.

1.1 Conversion of the diesel consumption profiles

The diesel consumption profiles used in this paper were created in the EkoTech research project [1] and represent a typical agricultural process chain in field cultivation. The process chain includes the agricultural processes soil tillage, sowing, plant protection, fertilisation and harvesting. While three agricultural machines are used simultaneously for harvesting (harvester and two tractors for transporting the harvest), only one agricultural machine is used at a time for the other processes. The use of diesel consumption profiles offers the advantage of using both simulated consumption profiles as well as measured consumption profiles. By using time series instead of static data, the varying power requirements of the individual processes can be realistically represented and process-dependent statements can be made regarding the machine concept to be used and the necessary parameterisation of the agricultural machine. The conversion to an electric power profile is done by using the calorific value of diesel H_i and overall efficiency of the diesel-powered drive train η_{CM} with P_{EM} representing the power consumption of the electric drive train and b_e representing the diesel consumption rate:

$$P_{EM} = b_e \cdot H_i \cdot \eta_{CM} \quad (1)$$

With the calorific value of diesel of 9.86 kWh/l and an assumed static efficiency of the diesel-powered drive train of 30 %, the electric motor output, shown in Figure 2 for the process soil tillage, is obtained. Depending on the agricultural process, the energy and power requirements of the agricultural machines vary greatly. Particularly in field cultivation, many processes are associated with a high energy input. Machines used for soil tillage, sowing and as harvester in harvesting have

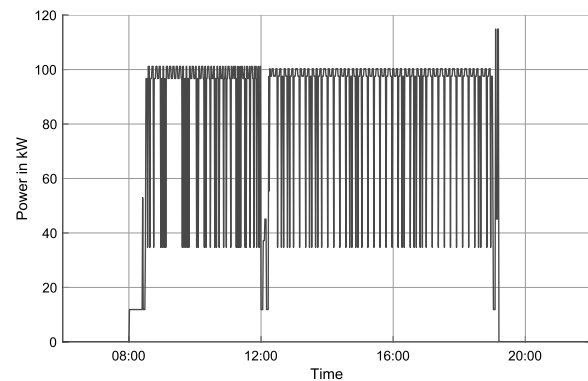


Figure 2: Resulting power consumption P_{EM} of the electric drive train during soil tillage.

a high energy consumption of up to 1 MWh per day, while other processes have a comparatively low energy consumption (e.g. the resulting electrical energy consumption for one tractor for transporting the harvest is 115 kWh per day). Due to the different requirements it is essential to consider different machine concepts with different parameterization for all-electric agricultural machines.

1.2 Battery-powered agricultural machine

Battery-powered agricultural machines draw their energy from a battery system, which can be installed in the machine or as exchangeable front/back weight. The advantage of the battery-powered concept lies in its unlimited mobility and the possibility of bidirectional charging.

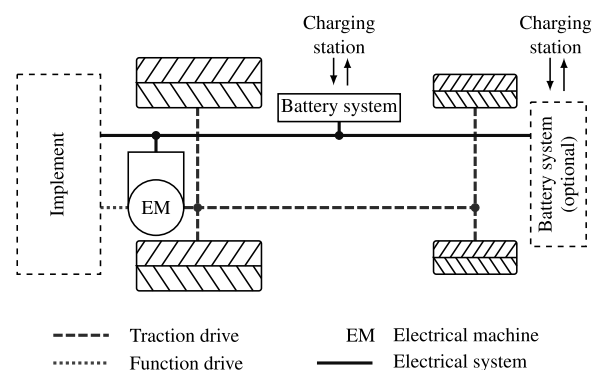


Figure 3: Possible machine concept of a battery-powered agricultural machine.

The battery-powered agricultural machine is modelled by a battery system which is discharged by the specified electrical consumption profile and recharged by a model of a charging station. The presence of the agri-

cultural machine and the maximum possible recharging time at the charging station is determined by the power consumption of the electric drive train P_{EM} . If no power is needed ($P_{EM} = 0$) it is assumed for simplification that the agricultural machine is at the charging station and has the possibility of recharging at the charging station's full nominal power. The presence of the agricultural machine at the charging station is described by the parameter appearance:

$$P_{EM} \begin{cases} > 0 \rightarrow \text{appearance} = 0 \\ = 0 \rightarrow \text{appearance} = 1 \end{cases} \quad (2)$$

The charging power at the charging station P_{charge} is calculated depending on the chosen charging strategy (*Charging with maximum power*, *Charging with minimum power*) and the maximum charging power of the battery system:

$$P_{charge} = \min \begin{cases} P_{bat,charge,max} \\ P_{charge,strategy} \end{cases} \quad (3)$$

$P_{bat,charge,max}$ is the maximum charging power of the battery system and $P_{charge,strategy}$ is the charging power set by the charging strategy. $P_{bat,charge,max}$ is calculated depending on the state-of-charge of the battery and is based on typical battery charging profiles. In the event that the actual state-of-charge is smaller than the state-of-charge at cut-off voltage, the charging power is calculated using the following equation:

$$P_{bat,charge,max} = \frac{C \cdot E_{bat,nom}}{\eta_{bat,charge}} \quad (4)$$

C is the charging/discharging rate, $E_{bat,nom}$ is the nominal battery capacity, E_{bat} is the available battery capacity and $\eta_{bat,charge}$ is the charging efficiency of the battery system. If the battery voltage reaches the cut-off voltage, the charging current is reduced at constant battery voltage, resulting in a reduced charging power. This effect is implemented by adjusting equation 4:

$$P_{bat,charge,max} = \frac{C \cdot E_{bat,nom}}{\eta_{bat,charge}} \cdot \left(\frac{SOC_{max} - SOC}{SOC_{max} - SOC_{cov}} \right) \quad (5)$$

SOC is the available state-of-charge, SOC_{max} is the maximum state-of-charge and SOC_{cov} is the state-of-charge at cut-off voltage.

In the case of the loading strategy *Charging with maximum power*, the agricultural machine is reloaded

with the nominal charging power of the charging station $P_{charge,nom}$ after completion of the field cultivation:

$$P_{charge,strategy} = P_{charge,max} = P_{charge,nom} \quad (6)$$

This charging strategy enables the agricultural machine to be recharged quickly, reducing the required idle time of the agricultural machine and increasing the potential operating time. The second charging strategy, *Charging with minimum power*, calculates the minimum charging power as a function of the total idle time $T_{appearance}$ as shown in the following equations and Figure 4.

$$E_{bat,dest} = E_{bat,nom} - E_{bat} \quad (7)$$

$$P_{charge,strategy} = P_{charge,min} = \frac{E_{bat,dest}}{T_{appearance} \cdot \eta_{charge}} \quad (8)$$

$E_{bat,dest}$ is the required battery capacity to be recharged, E_{bat} is the available battery capacity and $P_{charge,min}$ is the minimum charging power. This charging strategy is dependent on the next operating time of the agricultural machine and potentially reduces load peaks by recharging evenly over the entire idle time of the agricultural machine.

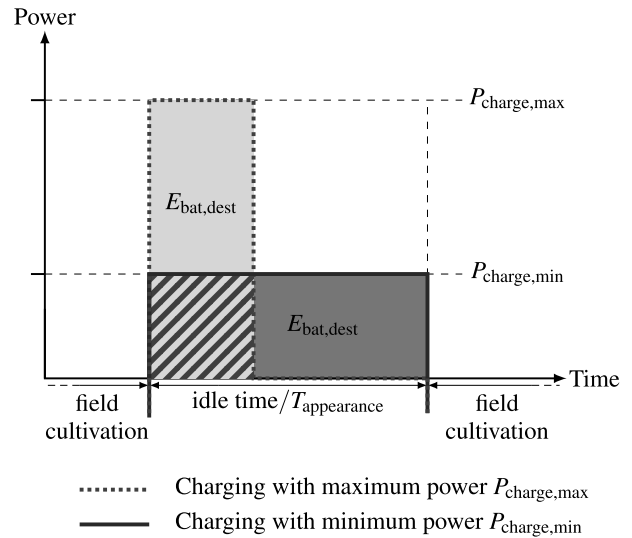


Figure 4: Influence of the charging strategies on charging power and time.

For the discharge power of the battery system, it is assumed for simplification that the power consumption P_{EM} can be covered at any time. This assumption is sufficient, as it can be assumed that only agricultural machines that can provide the required electrical power are used.

1.3 Grid-connected agricultural machine

Grid-connected agricultural machines are continuously supplied with energy via a power cable and do not have their own energy storage. Higher theoretical engine power is advantageous than with battery-powered agricultural machines, but mobility is restricted due to the cable, which is why this concept is not suitable for every agricultural process. The concept is particularly suitable for the power-intensive soil tillage and for the harvester in harvesting. In contrast to the battery-powered agricultural machine, the engine power P_{EM} is directly transmitted as output power P_{el} to the energy management.

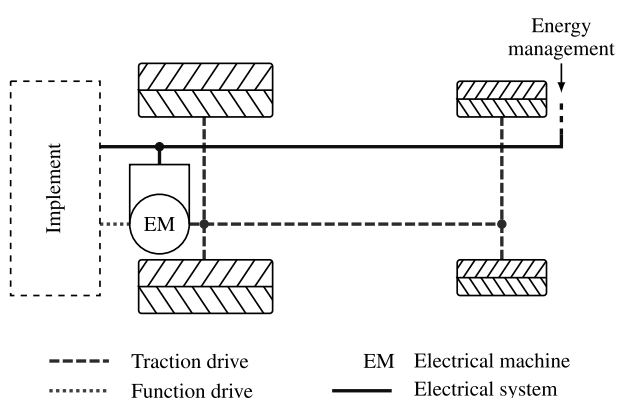


Figure 5: Machine concept of a grid-connected agricultural machine.

2 Modelling of the Renewable Electric Power System

All-electric agricultural machines can be supplied with energy from renewable energy plants operated by agricultural operations or from the power grid. To assess the effects of the integration of these machines and to derive suitable energy supply concepts, the modelling of the plants under consideration is necessary. In the following, the modelling of the photovoltaic plant, wind power plant and biogas plant as considered renewable energies, as well as the energy management and power grid, is briefly explained.

2.1 Renewable Energies

The photovoltaic model builds on the work already done in [2] and is based on a physics-based modelling approach. Weather data (solar radiation, solar azimuth,

solar altitude, outdoor temperature and cloud cover) from the test reference year of the German weather service [3] and serve as input data.

A data-based modelling approach as shown in Figure 6, is chosen for the wind turbine model, in which the generation capacity is calculated based on weather data from [4] and wind power curves from product data sheets of wind turbine manufacturers (e.g. [5])

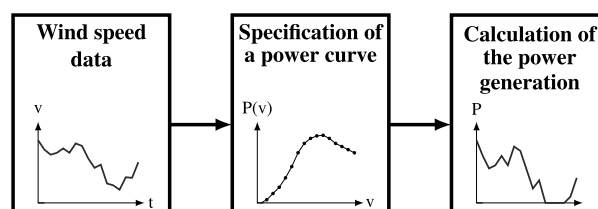


Figure 6: Data-driven modelling approach of the wind power plant.

The biogas plant is modelled in a simplified way using the load profile E0 of E-Control (Austrian government regulator for electricity and gas) [6]. This simplification is possible if biogas plants are operated at constant generation capacity without a flexibility option.

2.2 Energy management and power grid

The energy management serves as a superordinate control system of the power flows between the individual models on the farm and provides the interface to the power grid. The control process aims to maximise the internal consumption of the energy generated by the renewable energies and thus reduce the amount of energy supplied by the grid.

The grid calculation is carried out with the help of MATPOWER [7]. MATPOWER calculates the power flow with the grid structure and generator and consumption power as input data. The grid results can then be analysed and visualised in MATLAB and required and suitable grid optimisation and reinforcement measures can be determined.

3 Simulation Environment

The modelling of the technical components (Chapter 2) and the simulation studies (Chapter 4) are carried out in the institute's simulation environment eSE (elenia Simulation Environment) [8]. eSE is a MATLAB-based simulation environment for the scientific investigation of electrical and thermal systems and their behavior. In

addition, a flexible signal coupling of individual devices enables the investigation of connected systems and the testing of control concepts.

The simulation environment is divided into different modules, which can be used independently or in combination. The connection between all modules is the Simulator, which is represented by a single MATLAB class. It controls the information flow between the modules and takes over the central data management. The result of a simulation is a collection of time series of individual information flows and physical parameters of the devices, which can then be analyzed and evaluated. Figure 7 shows the three paths of the simulation process in eSE.

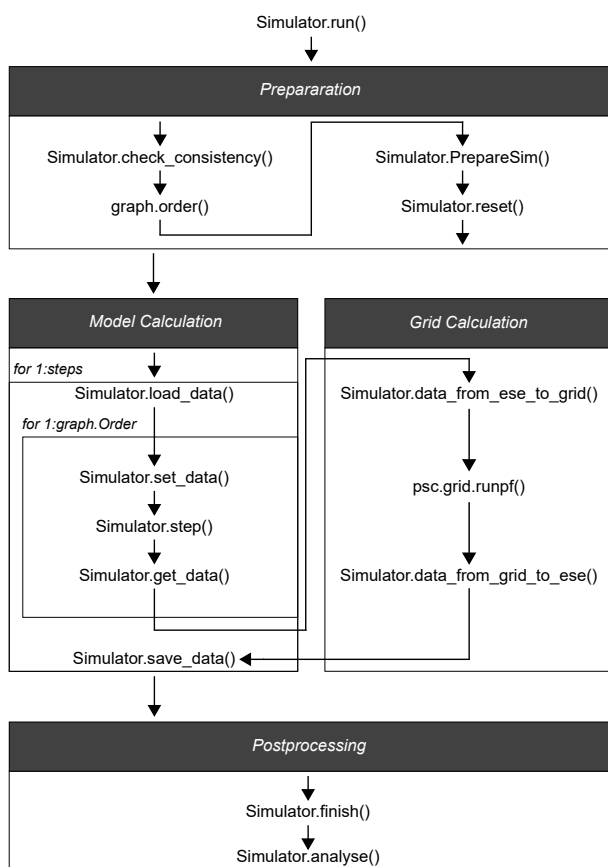


Figure 7: Simulation process in eSE.

In the preparation step, the simulation is checked for consistency and possible errors and automatically repaired if necessary. Afterwards a directed graph is created, which indicates the simulation order of the models by means of a topological search algorithm. Before all models are reset to a valid initial state, the simulation is prepared. During the preparation, model relationships

are stored temporarily in a local data structure to avoid database queries during the simulation.

At the beginning of each simulation step, stored external data sets are reloaded from an HDF5 file. Subsequently, three methods are executed for each model step. Before the model calculation, data from other models or external data sets are assigned to the model. Then the model with the functional relationships is calculated and result values are queried afterwards. The result values for active and reactive power are used as input values for the grid calculation to perform the load flow calculation with MATPOWER. The resulting values of the grid resources are finally queried and stored together with the model results in the HDF5 file for time series.

In the final phase, defined key indicators of time series and model properties are calculated and stored in an SQLite database. In addition, economic calculations of stakeholders and models are executed.

4 Simulation Scenarios and Results

To assess the power grid integration for all-electric agricultural machines, several simulation scenarios are considered and compared with each other. The simulation scenarios differ according to the power grid connection level of the agricultural enterprise (low voltage or medium voltage) and the selected charging strategy (*Charging with minimum power*, *Charging with maximum power*), resulting in four simulation scenarios. Due to the differentiation at the power grid connection level, different compositions of renewable energies are considered for the scenarios. The selected parameterization is shown in Table 1.

Model	Low voltage scenarios	Medium voltage scenarios
Photovoltaic plant	30 kW	100 kW
Wind power plant	-	100 kW
Biogas plant	-	75 kW
Charging Station	50 kW	300 kW
Battery-powered machines	1x260 kWh 1x600 kWh	1x260 kWh 1x600 kWh
Grid-connected machines	2	2

Table 1: Parameterization of the simulation scenarios.

For all scenarios, four all-electric agricultural machines are considered, whereby two are battery-powered with built-in batteries (used in fertilization, sowing and harvest) and two are grid-connected (used in soil tillage and harvest). The inclusion of four agricultural machines in the scenario enables a realistic representation of agricultural machines needed for a typical process chain in field cultivation. The battery-powered agricultural machines can be recharged after completion of the field cultivation at one charging station. A realistic annual load profile from a measurement campaign on a dairy farm is used as base load to model the remaining electricity consumption of the agricultural operation [9].

The low voltage distribution grid is represented by Kerber's *Landnetz Kabel 1* benchmark power grid and supplies five agricultural operations and three households [10]. The medium voltage distribution grid used is the CIGRE benchmark grid, where at load nodes 8 and 11 an agricultural operations is considered [11]. The remaining load nodes are mapped with standard load profiles for households and businesses [12].

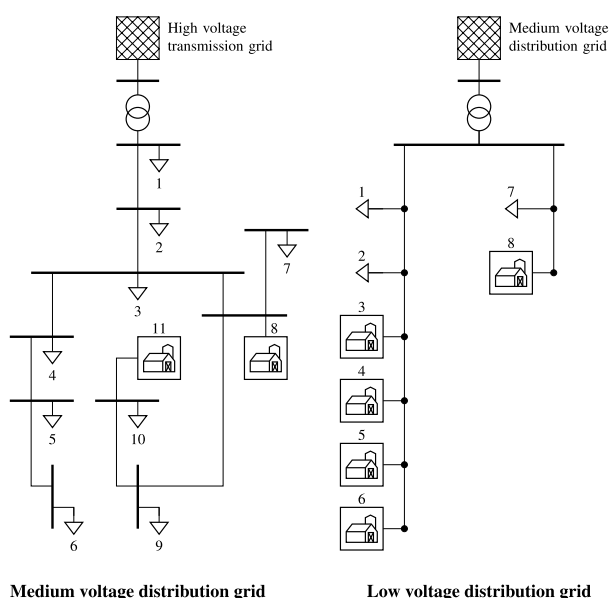


Figure 8: Structure of the modelled distribution grids.

The simulation is carried out using nine randomly selected type days distributed over an entire year, which allows seasonally dependent fluctuations in generation and consumption to be depicted and meaningful results to be obtained for the entire year. The type days cover arbitrarily selected agricultural processes with each agricultural machine being used at least once. The

Season	Day	Frequency per year	Agricultural process
Winter	13.03.	100	Fertilization
	23.11.	20	-
	03.02.	20	Plant protection
Summer	14.08.	88	Harvest
	03.08.	18	Soil tillage
	26.05.	17	-
Transition	09.04.	73	-
	20.04.	14	Fertilization
	15.09.	15	Sowing

Table 2: Chosen type days for the simulation.

frequency of the type days does not necessarily correspond to the whole duration of the agricultural processes, but since the agricultural machines are mostly used for further agricultural work, the selection of processes and allocation to the type days is assumed to be sufficiently accurate.

4.1 Technical results

The simulated agricultural operation with low voltage power grid connection shows an average own consumption of 39 % and an average self-sufficiency of 17 % when using the charging strategy *Charging with maximum power*. On days without the use of all-electric

	Charging max. Power	Charging min. Power
Own consumption	39 %	39 % ➡
Self-sufficiency	17 %	18 % ⬆
max. power grid supply	212 kW	188 kW ⬇
max. power grid feed-in	22 kW	22 kW ➡

Table 3: Technical results for the agricultural operations with low voltage power grid connection.

agricultural machines, but with a high level of renewable energy production, there are feed-in capacities of up to a maximum of 22 kW. On days with usage of all-electric agricultural machines and low regenerative energy production, a grid supply of up to 212 kW is required. By using the charging strategy *Charging with minimum power*, the own consumption and self-sufficiency do not increase significantly, as the charging

times of the battery-powered agricultural machines are outside the generation times of the photovoltaic plant for both charging strategies.

	Charging max. Power	Charging min. Power
Own consumption	17 %	18 % ➡
Self-sufficiency	70 %	98 % ⬆
max. power grid supply	233 kW	123 kW ⬇
max. power grid feed-in	178 kW	178 kW ➡

Table 4: Technical results for the agricultural operations with medium voltage power grid connection.

In the two scenarios with grid connection to the medium voltage distribution grid, the degree of self-sufficiency can be significantly increased, which can be attributed to the additional consideration of a biogas plant and wind power plant and the increased nominal capacity of the photovoltaic plant. Using the charging strategy *Charging with minimum power* instead of *Charging with maximum power*, the degree of self-sufficiency can be increased to nearly 100 %, since the generation capacity of the biogas plant and wind power plant can cover the entire consumption capacity more frequently (cf. Figure 9).

For the scenarios considered, possible voltage band violations and thermal overloads in the power grid are examined. The voltage applied to the network nodes in the power grid changes depending on the connected loads, generation plants and the location in the power grid. The permitted deviations from the nominal voltage are defined in DIN EN 50160 [13].

The thermal load capacity of the power grid elements used is regarded as a further key figure for determining the condition of the power grid. The nominal load capacity of the equipment is often specified in the associated data sheets and is assumed to be the limit value in the following.

	Charging max. Power	Charging min. Power
Voltage range deviations	18 %	18 % ➡
Thermal overload	21 %	18 % ⬇

Table 5: Frequency of limit violations in the low voltage power grid per year.

Table 5 shows the results for the low voltage distribution

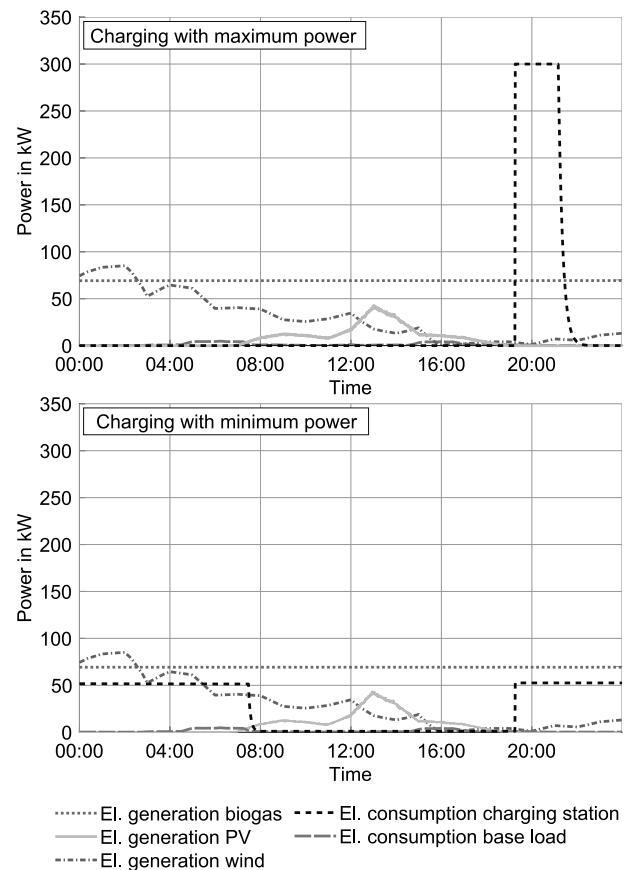


Figure 9: Electrical generation and consumption of different models on 15. September during sowing.

grid. In both scenarios with connection to the low voltage distribution grid, voltage band violations and equipment overloads occur on almost every power grid element, whereby the frequency of equipment overloads per year is slightly reduced by using the charging strategy *Charging with minimum power* compared to *Charging with maximum power*. Due to the limit value violations in the low voltage power grid and the maximum power grid supply of the individual agricultural operations, it can be useful to change the grid connection level of these operations to medium voltage. The medium voltage distribution grid did not show any limit value violations in the two scenarios with connection to the medium voltage distribution grid and is therefore suitable for agricultural operations with a previous connection to the low voltage distribution grid as a possible grid integration solution for all-electric agricultural machines.

5 Conclusion and Future Plans

This paper describes preliminary studies for the research project “Concept and modeling of agricultural systems with renewable energy supply - Energy-4-Agri”. The development and evaluation of energy supply concepts for all-electric agricultural machines requires a holistic modelling of the involved technologies. This paper therefore provides information on the modelling and simulation of the technologies and energy systems.

Diesel consumption profiles were chosen as input data set for the all-electric agricultural machines. The conversion to electric power values can only be seen as a first approximation given a dynamic efficiency of combustion engines. Further research is therefore needed in the development of electric power profiles for all-electric agricultural machines, which take into account dynamic efficiency of the internal combustion engine and can thus provide more accurate simulation results. It has been shown that the charging strategy *Charging with minimum power* can already reduce the grid load in contrast to *Charging with maximum power* and increase the degree of self-sufficiency. In the future, further charging strategies can be modelled to determine the optimal charging times based on forecast data of the generation capacities of the renewable energies or depending on the power grid condition.

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