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Enhancing Synergy Effects Between The Electrification Of Agricultural Machines And Renewable Energy Deployment With Semi-Stationary Energy Storage In Rural Grids

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Abstract

Electrified agricultural machines allow for higher precision of farming operations, higher power density, easier compliance with emission regulations, lowest noise and have lower operating costs than combustion engines. For these reasons, agricultural machine manufacturers have started developing electrified agricultural machines which are supplied either by batteries or via an electric cable linking them to a power point at the field edge. The electric power needed for their supply challenges the technical limits of rural grids in a similar way as strong deployment of renewable energies (RE) does, but a combination of electrified machines and RE can reduce the need for grid extension, respectively allows for higher RE penetration rates and climate protection. In particular, high PV power generation coincides frequently with the power demand of electrified agricultural machines. This synergy can be enhanced by semi-stationary (relocatable) energy storages balancing energy flows between grid, loads and PV installation, and providing further services. Provision of primary balancing power for at least 10 weeks per year ensures profitable operation in almost all investigated situations.

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Keywords: electrified agricultural machines; stationary energy storage; grid-storage trade-off; PV;

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1. Electrifying agricultural machines: a prerequisite for precision farming

Agricultural machine manufacturers have started developing partly and fully electrified agricultural machines (tractors and others) which are supplied either by an on-board generator driven by a combustion engine, batteries or via an electric cable linking them to a power point at the field edge. The main driver for electrification is precision farming which has the potential for drastically reducing the need for plant protection and mineral fertilization as these products can be brought on the field in better relation to the need which might vary strongly even over short distances. Weeds might even be removed mechanically without any use of chemicals if the machines operate with a precision of a few centimeters. This cannot be achieved with hydraulic drives used by today's agricultural machines which are propelled by diesel combustion engines. Hence, electrification is a prerequisite of precision farming.

Other motifs for electrification of agricultural machines are the potential for energy saving, higher power density, easier compliance with emission regulations, lower noise and lower operating costs compared to combustion engines. Further, the high potential of farms to generate electricity from renewable sources and to provide motive force at lower cost than diesel engines encourages manufacturers to go electric.

Up to now, agricultural machines with electrified auxiliary units (ventilation etc.) have been introduced on the market, while electrified implements, hybrid and fully electrified machines are still at experimental stage and will most likely deploy their full potential in connection with 24/24 h automated / autonomous operation which requires lower power due to a longer operation time. [1] Nevertheless, the high power demand of fully electrified agricultural machines, either for battery recharging or for direct supply via a cable connecting the machine to the field edge, remains a big challenge for rural grids. At this point, direct local power generation from renewable sources and accommodation of the power flows via a stationary energy storage come into play.

2. Case of a battery-electric machine

Fully battery-electric agricultural machines are suitable for operations at low load close to a charging point. This predestines them for livestock farms. Within a simple excel-based model calculation, a fully electric tractor with a 130 kWh lithium-ion traction battery was investigated for operation on a typical livestock farm with an annual electricity demand of 138 MWh and a peak demand of 143 kW. [2] The farm's base electricity demand is assumed to follow the L1 standard profile, while a PV installation on the farm follows the ES0 profile. The L1 standard profile is characterized by the electricity demand for non-automated milking and cooling and shows two pronounced peaks, one in the morning the other in the evening. It uses the grid rather inefficiently. Battery charging comes on top of the L1 profile with a maximum additional power of 50 kW and for a minimum time of 3 h for a full charge, either during the night and/or during a midday break.

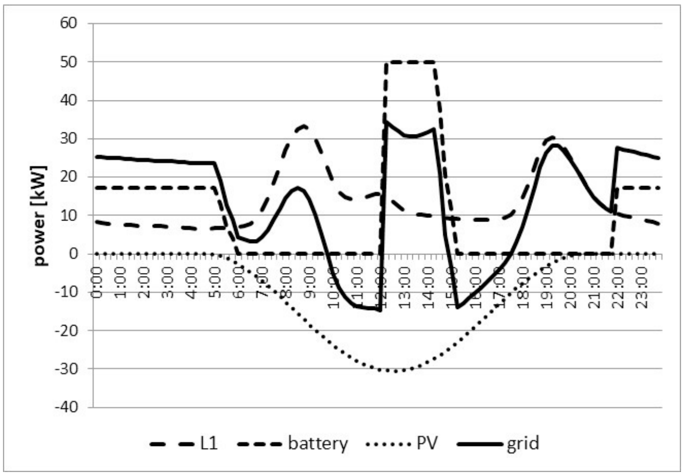

Fig. 1. Power flows of farm with battery charging and size-optimized PV installation

The results confirm that the charging power exceeds the grid connection capacity of many farms. The need for grid reinforcement however, can be limited if a PV installation is connected on the farm. The optimum size of a PV installation complementing the modelled farm and battery charging was determined for an average day in August. The closer its nominal power is to the maximum charging power of the electrified agricultural machine, the better. Overall, the grid connection capacity is much more efficiently used as shown in Figure 1 for a combination of the modelled farm with a 50 kW battery charging point and a 50 kWp PV installation. If only the battery charging for the agricultural machine was added, the maximum power drawn from the grid would be higher than before, necessitating maybe a grid reinforcement. This is avoided by adding also a PV installation such that the maximum power flow remains the same as before. [3]

Further improvement can be achieved if the traction battery pack can be easily taken off and on and two battery packages allow for charging one while the tractor is powered by the other. Also, an additional stationary battery can improve the flexibility of operations.

3. Case of a cable-electric machine

Cable-electric agricultural machines are currently investigated for very high-power operations on fields. The required power exceeds not only the connection capacity of most farms to the local grid, but also that of most rural local grids to the up-stream grid and of the up-stream grid itself. Hence, a model of an entire local rural grid was developed supplying a 1.2 MW agricultural machine in addition to other consumers which follow the L2 standard profile for arable farms, and PV installations which follow the ES0 standard profile. The model has been implemented in the open energy modelling framework (oemof). oemof is a python-based open source software library including a free solver which uses mixed-integer linear programming for optimizing energy systems. [4]

Calculations have been made to determine the optimum combination of grid (local transformer + respective share of up-stream grid across all voltage levels), energy storage, and PV curtailment for different annual base load and PV electricity generation levels, and for a given agricultural machine all-year operation scenario with a total consumption of 1,689 MWh, including heavy load operations (ploughing) in winter. Energy needed, but not generated locally within the same 15-minutes interval has been considered to be provided by an “unlimited residual generator” at a “far point” in the up-stream electric grid. Energy generated, but not needed locally has been considered to be consumed by an “unlimited residual consumer” at another “far point”. The “far points” were defined as locations positioned such that 6.85 % of energy transmitted between them and the local grid gets lost. This corresponds to the average loss rate between generators and consumers within the German electricity grid. The local grid has been modelled as a “copper-plate” without any restrictions to power flows and losses.

Costs and income considered in the objective function included grid and battery investment and fixed operation costs, costs of curtailed PV energy, costs of energy which is lost through grid transmission or storage, and income generated from using the storage for provision of primary frequency response (PR).

Different situations have been parametrized by (1) the electricity demand of all consumers connected to the local grid except the agricultural machine (annual base demand) and (2) the PV saturation rate. The latter has been defined in order to classify different levels of PV generation in relation to the annual base demand in local grids. It takes the value of 100 % when there is at least one 15-minutes interval in a year in which the inverse power flow from the local grid to the up-stream grid equals the maximum local base load, but no 15-minutes interval in which it is higher. It corresponds to the limit for PV generation up to which no reinforcement of the transformer and the up-stream grid is needed if they were just sufficient to provide the base demand before PV plants were built. 200 % corresponds to the case when their capacity needs to be doubled, 300 % when it needs to be tripled, etc. The exact relation between base demand, installed PV capacity and PV saturation rate depends on the respective load and generation profiles. For the combination of L2 and ES0 profiles, a PV saturation rate of 234 % corresponds to the case that the annual PV generation equals the annual base demand, i.e. the case of 100 % local self-supply on the average. Further parameters are (standard values chosen for modelling in brackets): annual costs of grid (37.39 €/kW) and storage (36.57 €/kWh), income from PR (13 weeks à 3.000 €/MW), weighted average costs of capital (5 %), grid loss rate (6.85 %), economic cost of electricity which is lost (6.5 ct€/kWh, approximately the production costs of a PV-wind-electricity mix from installations set up between 2015 and 2020), state-of-charge interval of storage (10 % to 90 %), charging and discharging efficiencies (95 %), and self-discharge rate (2.5E-6 per 15 minutes). [5]

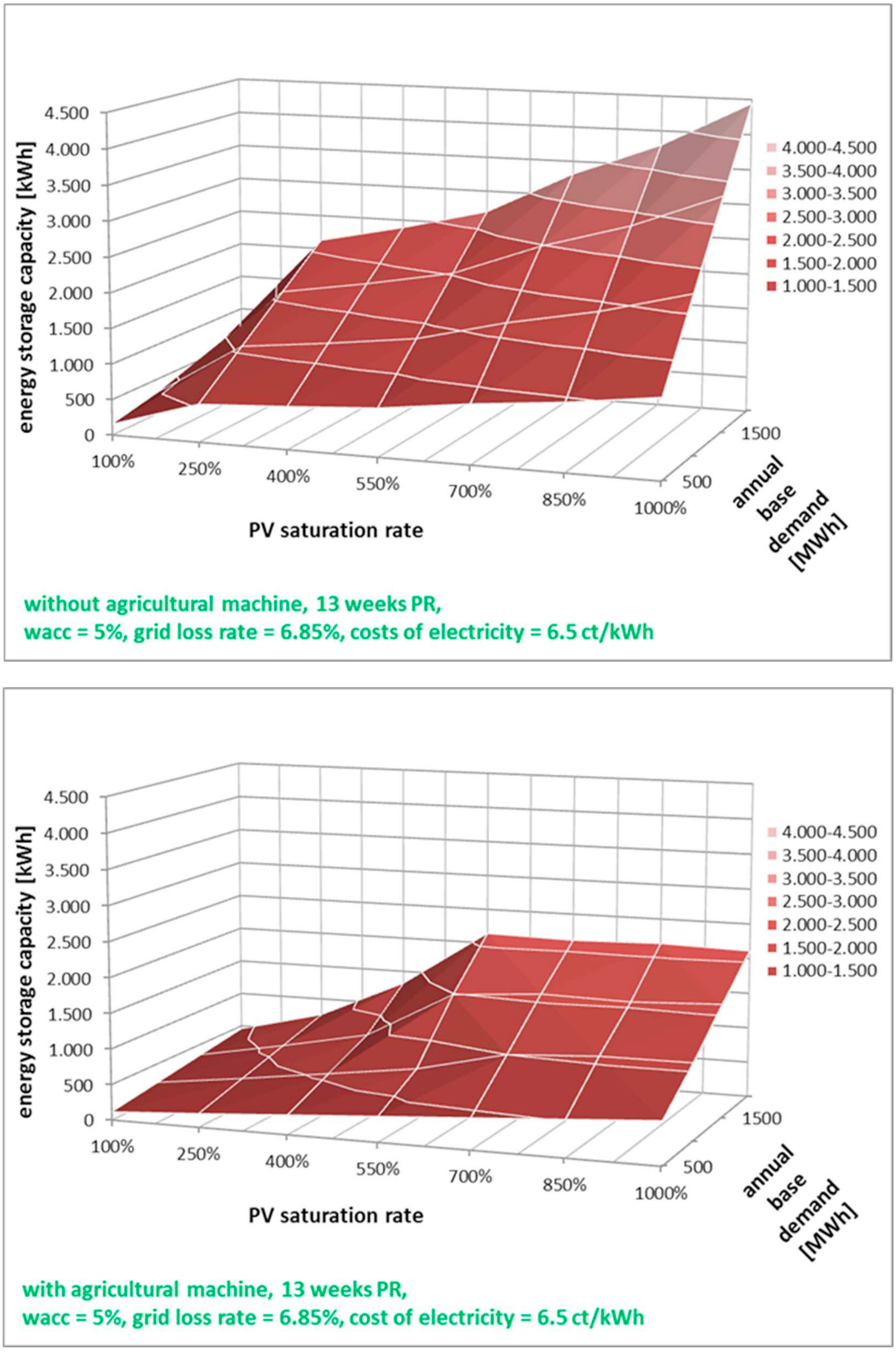

Fig. 2. Optimum size of energy storage without (above) and with (below) agricultural machine.

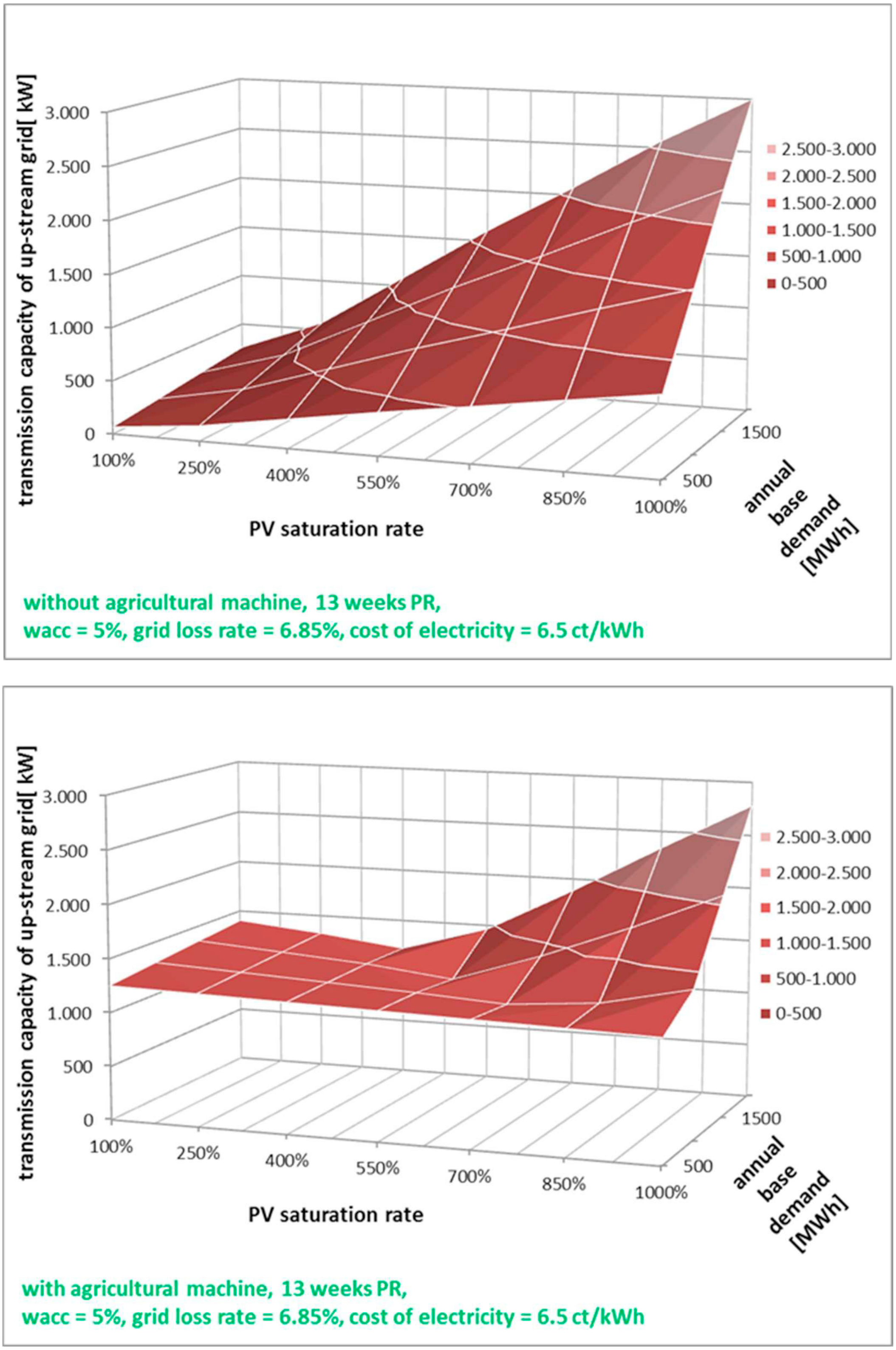

Fig. 3. Optimum size of transmission capacity of up-stream grid without (above) and with (below) agricultural machine.

Figure 2 shows the cost-optimal stationary energy storage capacity for different annual base demand and PV saturation rate without and with cable-electrified agricultural machine. Figure 3 shows correspondingly the cost-optimal up-stream grid transmission capacity. Without electrified agricultural machine, the optimum storage size increases with the base demand and PV saturation rate. It is noteworthy that a certain energy storage is always cost-optimal. Introducing the 1.2 MW electrified agricultural machine allows reducing the cost-optimal storage tremendously, especially at high PV saturation rate. This is because of the synergy between the high local demand created by the electrified agricultural machine and the high local PV generation. The maximum cost-optimal storage capacity is only slightly above 2 MWh, a capacity which can easily be accommodated in two 20-feet containers if lithium-ion batteries are used.

The cost-optimal up-stream grid transmission capacity increases almost linearly with the annual base demand and with the PV saturation rate. Introducing the 1.2 MW electrified agricultural machine requires in the cost-optimum case that the grid connection and further the up-stream grid transmission capacity is increased at least to 1.2 MW in almost all cases. However, at high annual base demand and high PV saturation rate, that is at very high PV generation, the cost-optimal up-stream grid transmission capacity is lower than without electrified agricultural machine.

Figure 4 shows the losses as a function of the PV saturation rate for an annual base demand of 1,000 MW and electrified agricultural machine for a cost-optimal combination of grid and storage. Grid losses are dominant though below 6.85 % as a part of the energy is generated and directly consumed locally. Storage losses can be neglected. It is noteworthy that up to a PV saturation rate of 550 %, which corresponds to about 200 % coverage of the local base demand by local PV generation on the average, no curtailment of PV generation is cost-optimal. At a PV saturation rate of 1,000 %, only curtailment of about 3.4 % of the total generation (local PV generation + residual generation which is transmitted via the grid) is cost-optimal which is equivalent to 10.7 % of the locally generated PV electricity. This indicates that except for a very high PV saturation rate, PV electricity can be well accommodated thanks to the synergy with the electrified agricultural machine and the energy storage.

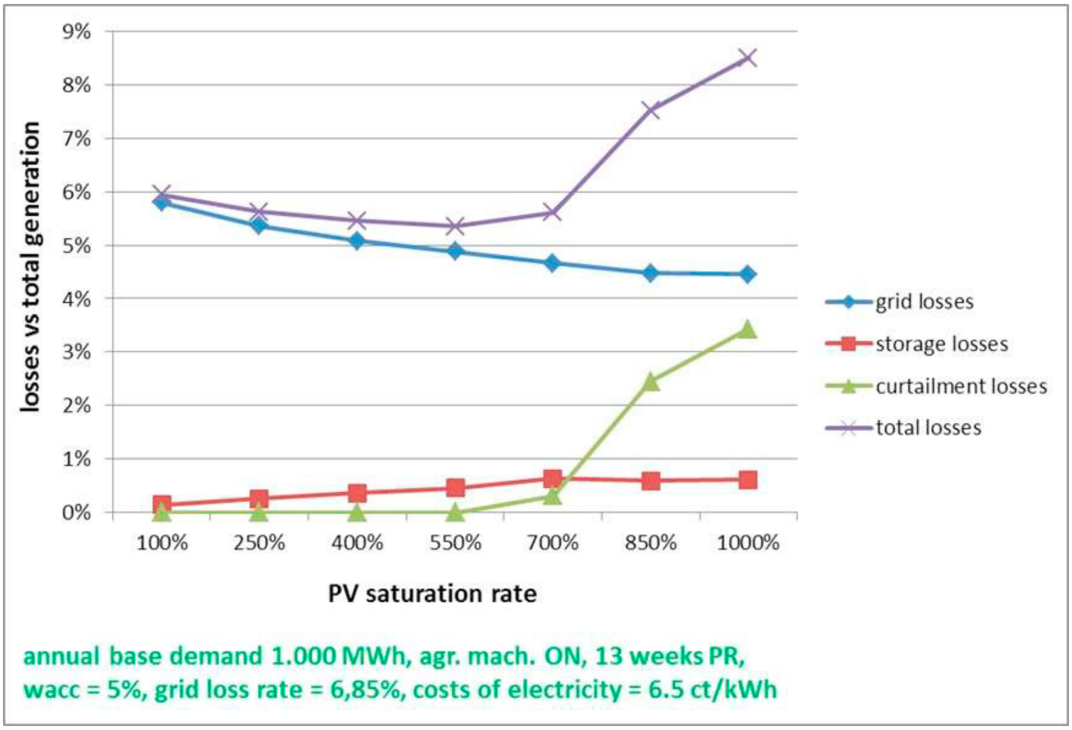

Fig. 4. Losses vs PV saturation rate for annual base demand of 1,000 MWh and electrified agricultural machine.

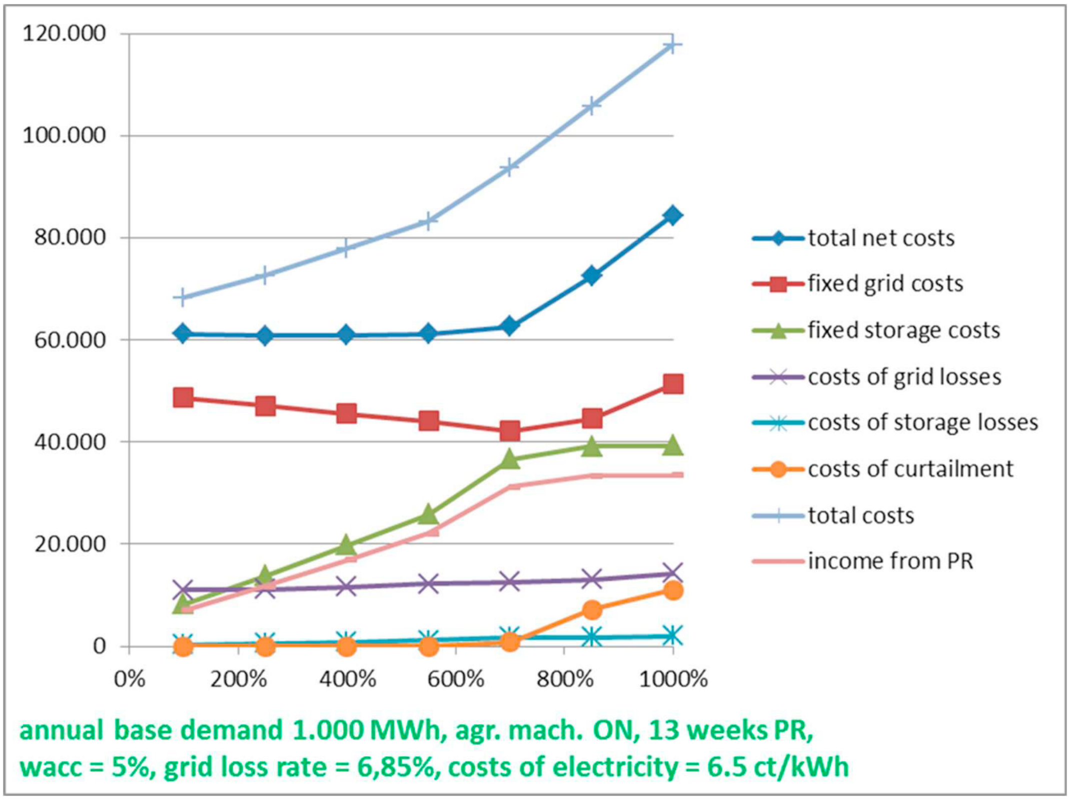

Fig. 5. Costs in € vs PV saturation rate for annual base demand of 1,000 MWh and electrified agricultural machine.

Figure 5 shows the costs and income from PR as a function of the PV saturation rate for an annual base demand of 1,000 MWh and agricultural machine for a cost-optimal combination of grid and storage. The strongest change is experienced by the storage cost and correspondingly the income from PR which are both proportional to the storage size. Up to a PV saturation rate of 700 % all other cost components vary little. From this, a strategy can be deduced for a situation in which an electrified agricultural machine is introduced in a local grid with little PV generation in the beginning: At first, the grid needs to be reinforced such that the electrified agricultural machine can be operated and a small storage needs to be installed. The grid is then sufficiently strong to accommodate a tremendous increase of PV generation up to a saturation rate of almost 1,000 %. Storage capacity can be successively added until a PV saturation rate of a bit more than 800 % can be accommodated. Further PV can be added until almost 1,000 % PV saturation is reached without any change of grid or storage with just a slightly higher PV curtailment.

A more detailed investigation of power flows during the course of the year shows that the energy storage is only used for a minor part of the time in most cases and in some of them there are even periods of days or even weeks in which it is not used at all. This shows that not only other services such as PR can be provided by an energy storage installed primarily to balance the power flows between grid, agricultural machine and PV installations, but also that the storage can be temporarily relocated to other sites in some cases. For this reason, this paper addresses semi-stationary storage instead of simply stationary storage.

4. Sensitivity analysis

Figure 6 shows the dependency of the cost-optimal storage capacity on the number of weeks for which income from PR provision is generated for an annual base demand of 1,000 MWh, a PV saturation rate of 400 % and with agricultural machine. It strikingly shows the importance of income generation from PR provision for a cost-effective operation of the storage. If less than 10 times per year 3,000 €/MW/week income is generated by PR provision, the installation of a storage is not cost-effective. If such income is generated for more than 13 weeks per year, the cost-optimal storage size rises dramatically.

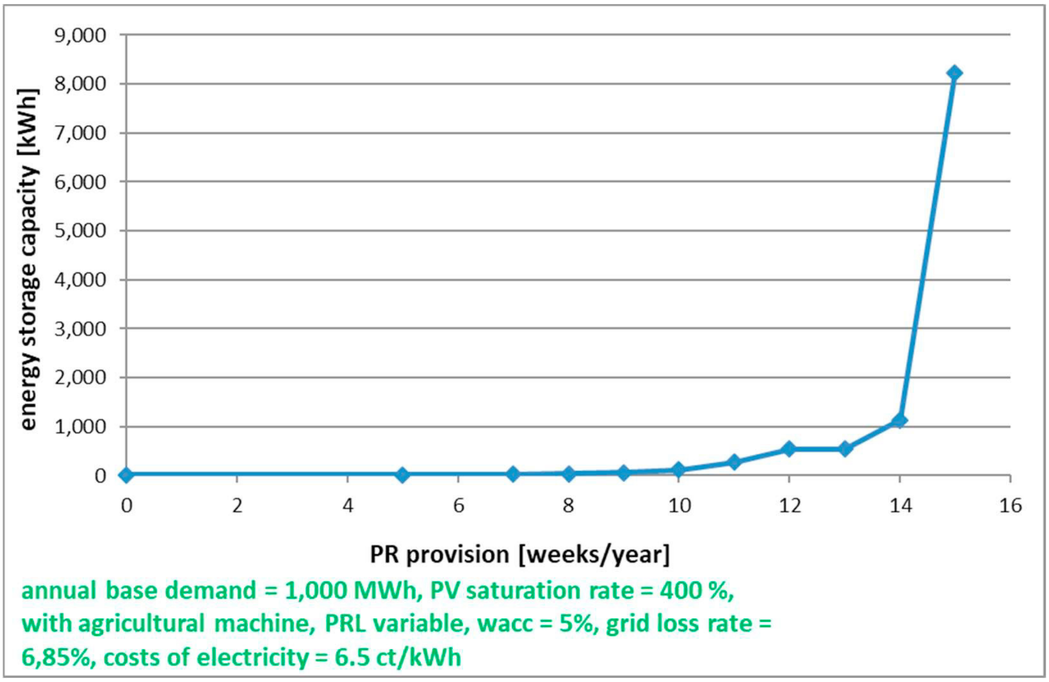

Fig. 6. Cost-optimal storage capacity vs number of weeks for which PR is provided.

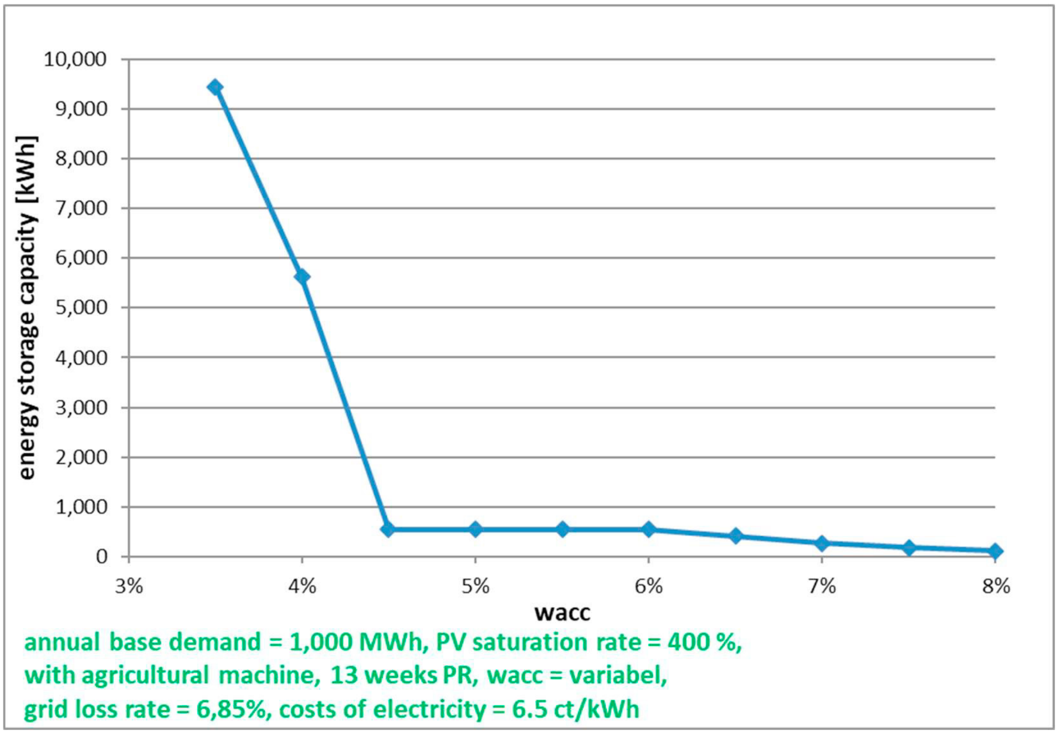

Fig. 7. Cost-optimal storage capacity vs weighted average cost of capital (wacc).

Figure 7 shows the cost-optimal storage capacity as a function of the weighted average cost of capital (wacc) for an annual base demand of 1,000 MWh, a PV saturation rate of 400 % and with agricultural machine. For a wide range of medium wacc between 4,5 % and 6 % there is no change and for higher wacc, it is more cost-effective to install a smaller storage and to increase the grid capacity instead. However, for smaller wacc than 4.5 %, the cost-optimal storage capacity is much larger than for medium wacc.

Further sensitivity analysis has been performed to investigate the influence of the specific cost (value) of electric energy which gets lost and the grid loss rate. If the specific cost of electric energy lost in the system increases, the optimal grid and storage capacities both increase, thus replacing part of additional OPEX by CAPEX. If the grid loss rate increases, the optimal grid connection capacity decreases and the optimal energy storage capacity increases, i.e. a more decentralized electricity supply becomes optimal. However, there is little change for grid loss rates between 0 and 20 %. [6]

5. Conclusions

The presented model calculations show that semi-stationary (relocatable) energy storage in rural grids can enhance the synergies between electrification of agricultural machines and renewable energy deployment and is a necessary ingredient of an optimal electricity supply infrastructure. The investment in the storage system pays back if it is used for providing PR for at least 10 weeks per year in addition to being used for balancing local energy flows. This couples the electricity sector to the mobility sector and facilitates a higher overall rate of renewable energy use and climate change abatement. The results are relevant beyond the agricultural sector and can be transferred to high-power electric mobile machine applications in other fields such as building and mining, or to charging stations for electric cars along motor ways in rural areas.

The lessons learnt from this work confirm that the overall cost of the electricity system can be reduced if a framework is created which facilitates the operation and multi-purpose use of grid-connected energy storage by a larger number of stakeholders, including farmers, agricultural machine rings and similar organizations. In particular, easier participation in the balancing energy markets is very helpful at this regard.

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