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

M. Stöhr[1], B. Hackenberg[2], B.A.U.M. Consult GmbH, München

1) m.stoehr@baumgroup.de 2) bastian.hackenberg@posteo.de
www.baumgroup.de, www.sesam-project.de, www.gridcon-project.de

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.

Case of a battery-electric machine

Fully battery-electric agricultural machines are basically suitable for operations at low load close to a charging point. This predestines them for livestock farms. Within a model calculation, a fully electric tractor with a 130 kWh lithium-ion traction battery was investigated which is operated on a dairy farm and recharged with a maximum power of 50 kW and a minimum time of 3 h for a full charge either during the night and/or during a midday break. The farm's base electric consumption follows the L1 standard profile, a PV installation on the farm the ES0 profile. The L1 standard profile represents dairy farms and shows two pronounced peaks, one in the morning the other in the evening, and uses grid connection capacity rather inefficiently. The results show 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 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. 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.

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. A model of a 1.2 MW agricultural machine operated in a local rural grid with other consumers than the machine following the L2 standard profile for farms without dairy production, and PV installations following the ES0 standard profile has been developed and implemented in the open energy modelling framework (OEMOF). Calculations have been made to determine the optimum combination of grid extension, storage size, and PV curtailment rate for different base load consumption and PV electricity generation levels, and a given agricultural machine all-year operation scenario with a total consumption of 1,689 MWh, including heavy load operations in winter.

Different situations were parametrised by (1) the annual electricity demand of all the other consumers than the agricultural machine connected to the local grid (annual base demand) and (2) the PV saturation rate. The latter has been defined in order to classify different levels of PV generation in comparison to the annual base demand in a local grid. It takes the value of 100 % when there is at least one 15 minute interval in a year in which the inverse power flow from the local grid up-stream grid equals the maximum load, but no 15 minute 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 for which a standard value has been fixed, and then varied within a sensitivity analysis, are: the number of weeks for which income from primary balancing power (primary reserve, PR) is generated (13 weeks), the weighted average costs of capital (5 %), the grid loss rate, i.e. the percentage of electricity lost when transmitted via the up-stream grid (6.85 %, that corresponds to the average loss rate within the German electricity grid), and the economic costs of electricity which is lost either when transmitted via the up-stream grid, or when stored locally, or by curtailment of PV generation (6.5 ct/kWh, approximately the production costs of a PV-wind-electricity mix from installations set up between 2015 and 2020). Other assumptions: the energy storage is operated between 10 % and 90 % of its nominal capacity. The charging and discharging efficiencies are, respectively, 95 % and the self-discharge rate 2.5E-6 per 15 minutes.

Figures 1 and 2 show the cost-optimal (up-stream) grid connection capacity for different base load demands and PV saturation rates for a situation, respectively, with cable-electrified agricultural machine and without. Figure 3 and 4 show correspondingly the cost-optimal stationary energy storage capacity.

A further result is that PV curtailment is rarely cost-optimal and, if, the optimal curtailment rate is almost always below 1 %. This value is below other estimates and shows that storage allows making almost complete use of PV generation. A few percent of curtailment start being cost-optimal at PV saturation rates above 700 %.

The energy storage is only used for a minor part of the time in most cases and in some situations 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.

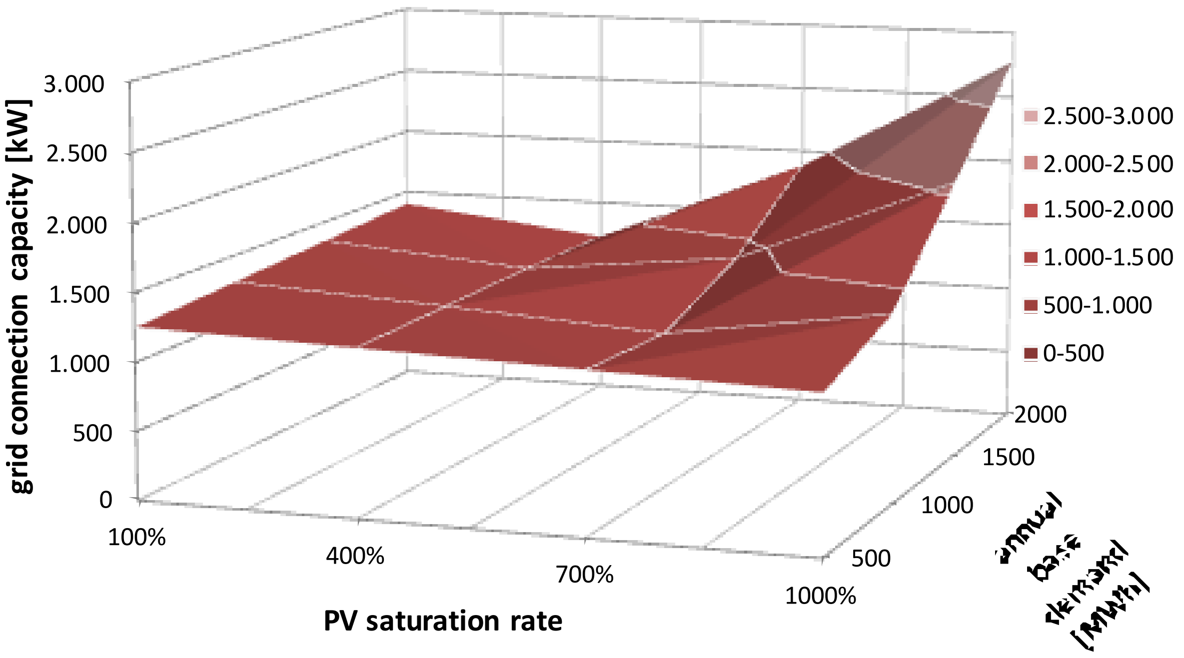

Figure1: with agricultural machine, 13 weeks PR,
wacc = 5%, grid loss rate = 6,85%, costs of electricity lost = 6.5 ct/kWh

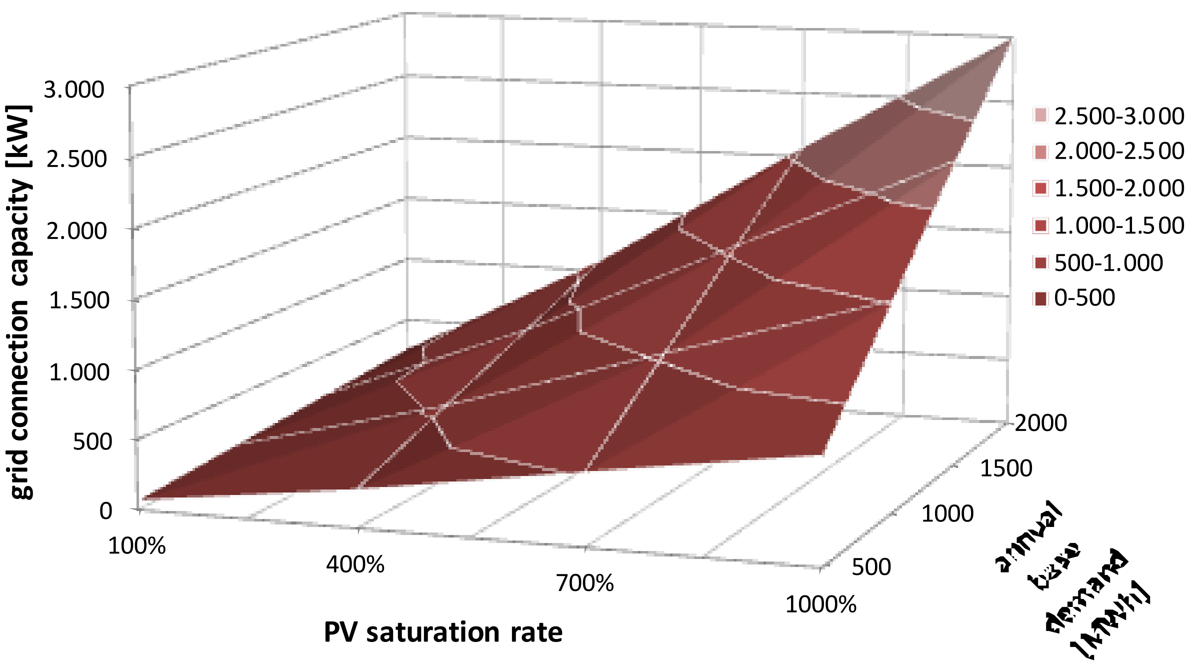

Figure 2: without agricultural machine, 13 weeks PR,
wacc = 5%, grid loss rate = 6,85%, costs of electricity lost = 6.5 ct/kWh

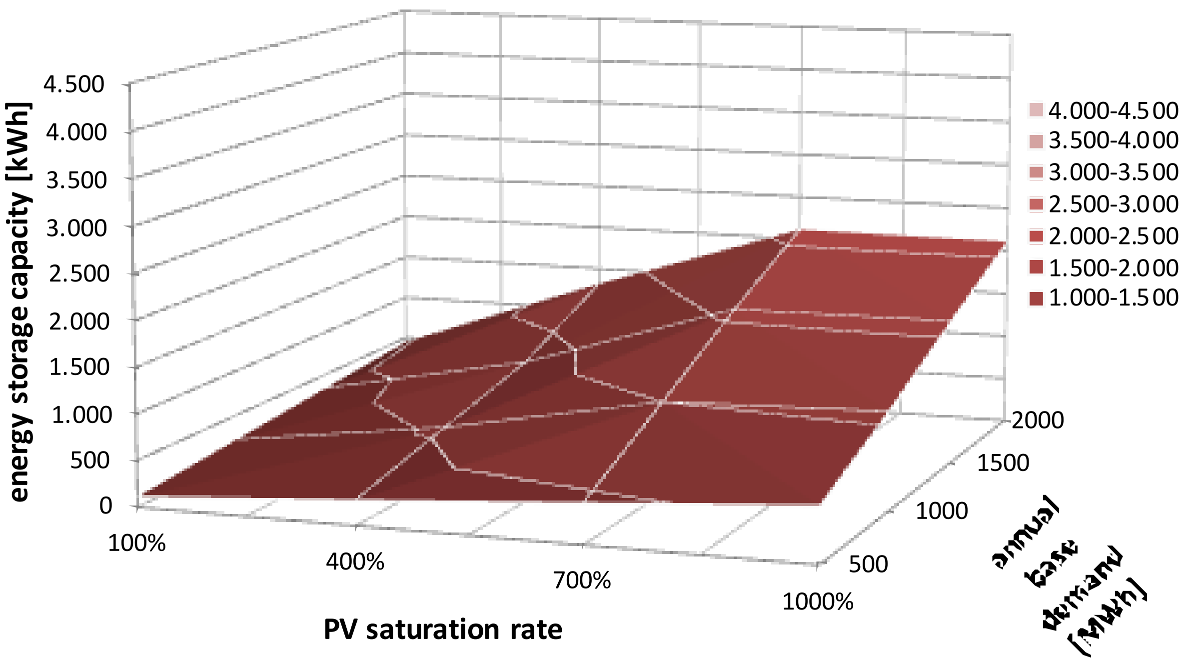

Figure 3: with agricultural machine, 13 weeks PR,
wacc = 5%, grid loss rate = 6,85%, costs of electricity lost = 6.5 ct/kWh

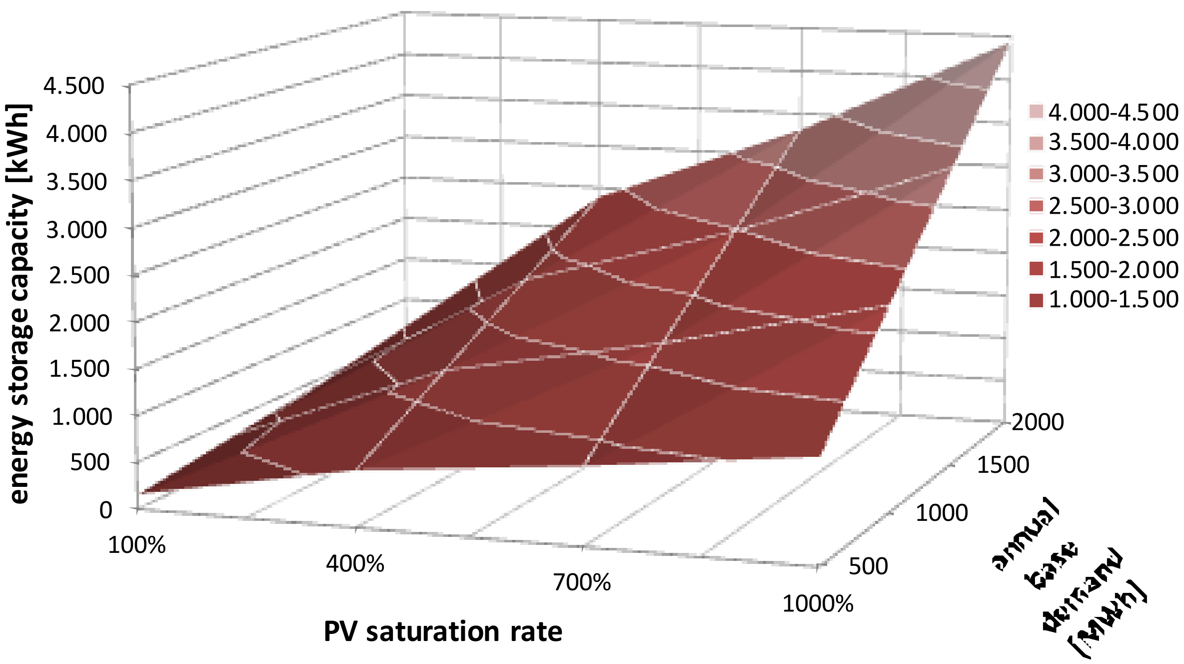

Figure 4: without agricultural machine, 13 weeks PR,
wacc = 5%, grid loss rate = 6,85%, costs of elctricity lost = 6.5 ct/kWh

Sensitivity analysis

The results show a strong dependency on the number of weeks for which income from PR provision is generated. If this is done for less than 10 weeks per year, it is generally not optimal to install energy storage, but rather a sufficiently powerful up-stream grid connection. The higher the weighted average costs of finance, wacc, the higher is the optimal grid connection capacity and the smaller the optimal energy storage. If the specific costs for electric energy lost in the system increase, the optimal grid connection capacity and the optimal energy storage capacity 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 is optimal. However, there is little change for grid loss rates between 0 and 20 %.

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 to the mobility sector and facilitates a higher overall rate of RE 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.

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