Modelling and optimization of renewable energy supply for electrified vehicle fleet

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ABSTRACT

The upcoming electric Mobility requires new concepts for recharging infrastructure. Vehicle fleets, especially in public sector or offices of inner-city companies, are desired to be equipped with hybrid or fully-electrified vehicles at first. To keep mobility costs affordable in an economic and ecological way, an adequate charging infrastructure has to provide a sufficient amount of renewable energy, for example produced by big photovoltaic systems and wind energy plants. Another possibility is to use locally produced renewable energy at the corresponding office building, for example by biogas-fired combined heat and power units. But what is the right configuration of such a complex energy system providing heat and electricity for building as well as vehicle fleet.

This paper presents a new simulation approach to simulate building's energy system behaviour together with energy needs of a partly electrified vehicle fleet. Therefore, EA Systems developed Modelica-based 'Green Building' library which enables the user to identify an overall optimized system configuration.

Keywords: Modelica, Green Building, Building simulation, Vehicle dynamics, Sustainable system layout, Renewable energy, Storage systems

INTRODUCTION AND MOTIVATION

Due to rapidly increasing fuel costs and upcoming governmental restrictions (c.f. European Union's carbon dioxide fleet emissions) to emissions vehicle manufacturers all over the world have developed solutions for hybrid-electric or fully-electrified vehicles for the last ten to fifteen years. That way, overall efficiency of vehicle power trains could be increased up to more than 80% using modern battery systems, low-loss power electronics as well as growing computational capacity.

Although, such vehicles cause low or zero emissions as well as significant reduction of energy consumptions high system complexity and component costs (c.f. lithium-ion-batteries) are responsible for comparably high vehicle costs at first. That way, first larger quantities will probably be sold to inner-city companies or public offices which can afford higher initial prizes with respect to comparatively high energy savings during the life span of the vehicles. Furthermore, mainly-inner-city usage enables alleviation of disadvantages regarding reduced operating range and comparatively long recharging times.

Therefore, an adequate charging infrastructure is needed. In case of a fleet, several vehicles have to be recharged depending on acceptable idle times, required operating ranges and available electrical power. Furthermore, to enable real zero-emissions mobility, vehicles' energy demand should be fulfilled using renewable energy resources and available storage capacities.

Such an intelligent charging infrastructure is a highly complex system which includes physical connection to several energy systems (e.g. photovoltaic system at office building) as well as integrated smart control algorithms (e.g. control interface, operating strategy). That way, system layout is a complex engineering task which requires dynamic simulation analysis. These analyses have to combine building and vehicle aspects as well as an adequate representation of relevant storage systems (e.g. batteries, heat storages, etc.).

There is a great variety of such simulation systems available for the different system types (building – vehicle) and domains (heat – electricity). Building simulations can be precisely done using TRNSYS or EnergyPlus. However, these simulation platforms allow simulation of thermal behaviour of rooms or buildings with high accuracy and resolution. Energy system behaviour in combination with building can be calculated using for example a tool-chain with TRSNYS and Matlab/Simulink. That way, also electrical building energy demand can be represented in an adequate way. Single energy systems, for example photovoltaic, can be analysed with domain- or system-specific programs as well, e.g. PVSol.

In automotive industry a wide range of simulation systems is used as well. Some representatives of adequate simulation approaches for hybrid-electric or fully-electrified vehicles are IAD's Modelica-based eVehicleLib [1] or ITI's Hybrid Powertrain package [5]. These can be used to precisely simulate vehicle and powertrain component behaviour depending on a chosen driving cycle.

However, there has not been an adequate simulation approach to combine vehicle simulations with heat and electricity consumption analyses in buildings, yet.

Therefore, EA Systems developed 'Green Building' simulation package enabling the user to analyse vehicle energy demand together with renewable energy availability, storage capacities and intelligent energy management algorithms.

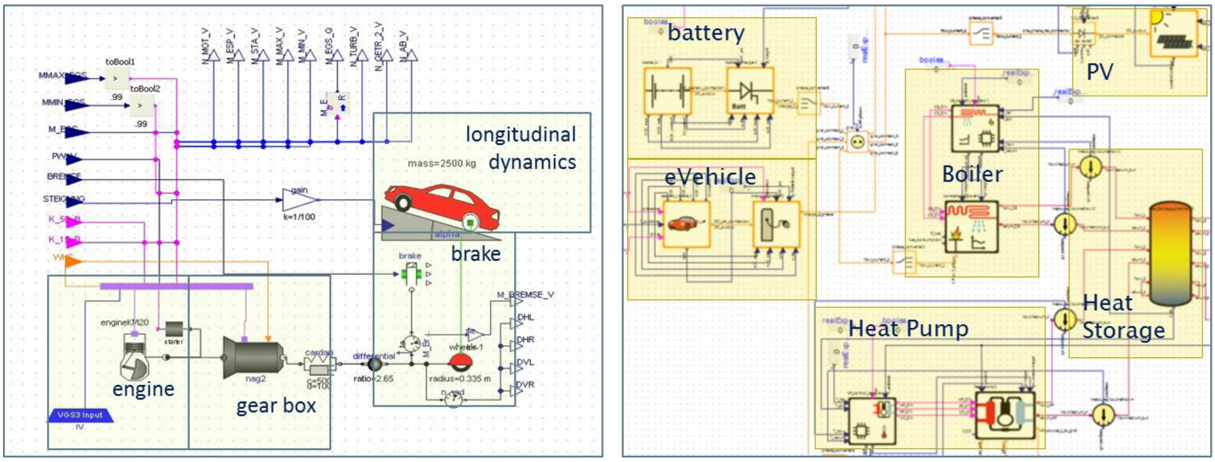

Fig. 1: Comparison of simulation approaches – vehicle components model and 'Green Building' components model [4]

It was derived from an approach widely used in automotive industry. Figure 1 shows this approach combining several power train component models (e.g. brakes, gear boxes, engine, etc.) to one complete vehicle models. 'Green Building' adapts such an approach to building energy system components (e.g. heat pump, heat storage). Furthermore, vehicles can be integrated as additional component model. That way, influences of vehicle's energy demand on building energy system behaviour can be easily analysed in one simulation platform.

SIMULATION PLATFORM

Green Building Simulation Package

Modelica is an equation based and domain-overall modelling language. That offers the possibility to model complex building energy systems with different domains (e.g. heat, electricity, control) using differential-algebraic equations. These equation systems can be edited and solved within one simulation environment.
That is why EA Systems used Modelica and the versatile simulation environment SimulationX™ to develop a new library for building energy system simulation (‘Green Building’). Thereby, an approach widely used in the automotive industry was adapted by creating several elements for renewable energy production and heating systems as well as storages and electrical or thermal consumers. Most of the models represent real world objects like vehicles, electrical inverters or valves. Thereby granularity and complexity of each element is in the same range, all in the objective of flexible yet easy modelling.
All these elements can be assembled to one complex building energy system model using domain-specific model connectors, for example [3]:

Thermal Connector: $$e_{therm}(t) = \int \rho_{med} \cdot c_{p_{med}} \cdot \dot{V}_{med} \cdot \Delta T_{med} \, dt \quad (1)$$

Electrical Connector: $$e_{el}(t) = \int U_{eff} \cdot I_{eff} \cdot \cos\varphi \cdot n_{phase} \, dt \quad (2)$$

Both equations (1) and (2) describe the interchanged energy between connected components during the simulation run. Each power connector consists of the domain-specific flow (volume flow and current) and potential (temperature spread and voltage) states as well as further special constant values. The connectors have subtypes to add versatility for example DC, AC or 3-Phase electrical link. Additionally, the library contains signal oriented connectors for environment and various control functions.
A special emphasis was placed on the input parameter set of each component model. A main objective is to use easy-to-get parameters like datasheet values as inputs instead of reference sheets or values which would be favourable from a more developer or numerical point of view. This way, the library design provides a more intuitive modelling of various building energy architectures.

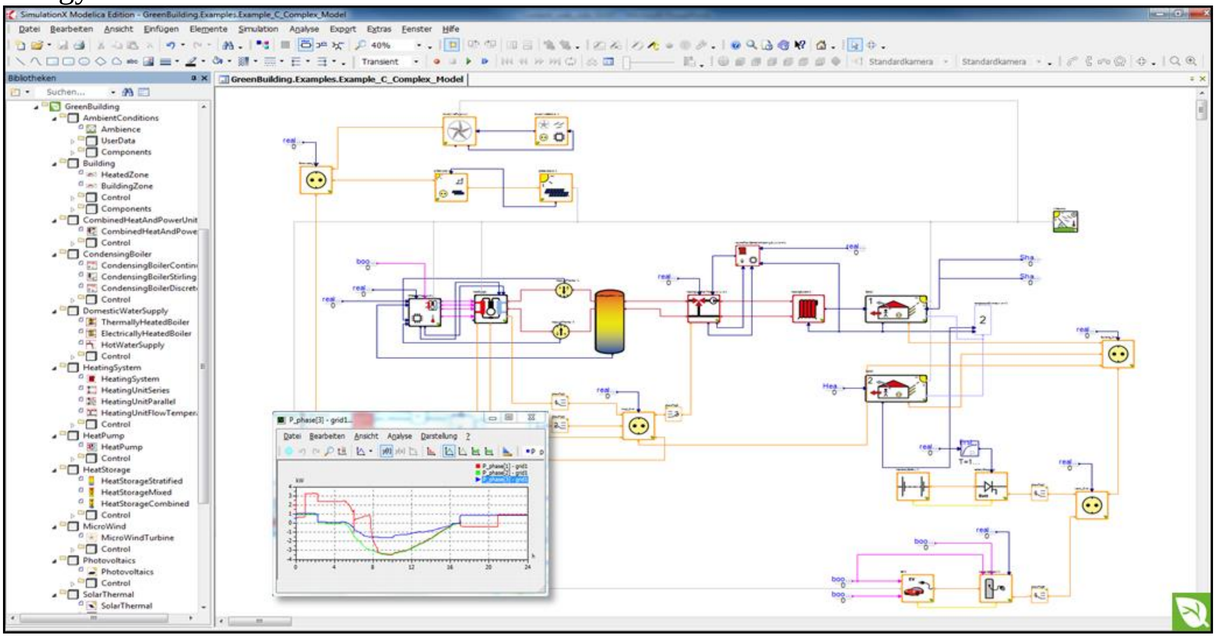

Fig. 2: Renewable energy system including e-Vehicle in the simulation environment

Another requirement to the chosen approach is that all the relevant characteristics needed for the comparison of different building energy systems, shall be calculated within the same simulation environment, if possible. Therefore, all library components consist of three parts. Physical or functional behaviour, control algorithms and external interrupt connectors for energy management. Based on the Modelica concept, each part is a differential-algebraic equation system (DAE). Information exchange is channelled through the connectors.
Optional functions to describe investment and operating costs of each component. However, these calculations are currently performed based on the simulation results in external post-processing routines which also contain the variant management.
Fast simulation speed is essential for effective analysis of many variants on optimization cycles. Still time resolution and error margin need to be kept low for a functioning control model. As a Benchmark for a valid comparison of different building energy systems a period of one year with a minimum time resolution of one minute is mainly used. So usage of a variable time step solver is essential. Additionally, the model detail is important. The library models all have similar detail. For example a stratified storage tank as a physical model consists of n layers with heat and matter exchange, heat loss to the outside and thermal absorption/dissipation for loading/unloading. Compared to real tanks this is correct for energy balancing and control algorithms (design goal of library). To get exact surface temperatures a CFD Simulation of all internal convection would be needed, which also would require much more processing time.
Therefore, it is necessary to reduce modelling accuracy for internal processes to a minimum. This applies especially to processes which have no or little impact on the interactive behaviour of the component. If it is not possible to obtain a fast physical model with the required accuracy, phenomenological models describing the white-box behaviour based on measured or pre-calculated operational points were used. A typical example is the micro-wind-turbine model, where the power output mainly depends on wind speed and most internal processes would be much faster than the simulation scale.
Another example of a phenomenological model is the heat power output of a heat pump depending on source temperature. These characteristics are included in the models as input parameter sets to be interpolated during the simulation depending on the simulated conditions.
Because the physical behaviour of some components highly depends on outer characteristics (e.g. electrical energy production of photovoltaic systems depending on solar radiation) these models use external data as input characteristics.
Control algorithms for the internal regulation of the components (e.g. de-icing processes of air heat pumps) are integrated in separate models. This way, easy-to-use standard controllers, are available (e.g. heat-led or electrical-led CHP). To analyse system behaviour these controllers have inputs for high level energy management algorithms (e.g. switch-on of CHP depending heat demand).
For more complex control strategies, the basic controllers can be replaced by whatever the user wants, using the full might of Modelica control and state-chart libraries.

Integration of dynamic vehicle behaviour

Main challenge in coupling building and vehicle dynamics simulation is the difference in major time constants. That way, using existing simulation approaches for both domains would cause small minimum simulation step sizes and very stiff differential-algebraic equation systems.
Thermal energy flow in buildings mainly depends on low system dynamics (c.f. temperature changes – about hours). The corresponding electrical energy behaviour is subject to much smaller time constants (about minutes). However, time constants of vehicle dynamics can even be in a range of seconds to milliseconds. As mentioned before, there are sufficient

approaches to simulate the dynamic system behaviour of vehicle powertrains depending on standardized (c.f. NEDC – New European driving cycle) or even more realistic driving cycles (c.f. ftp75). That way, even different electric or hybrid-electric powertrain architectures can be analysed with high accuracy.

However from a building point of view only vehicle's overall energy consumption (fuel, electricity, recuperation, etc.) is important. Furthermore, to define realistic and suitable charging strategies some information about vehicle's presence at the charging station as well as required energy demand for following trips are needed.

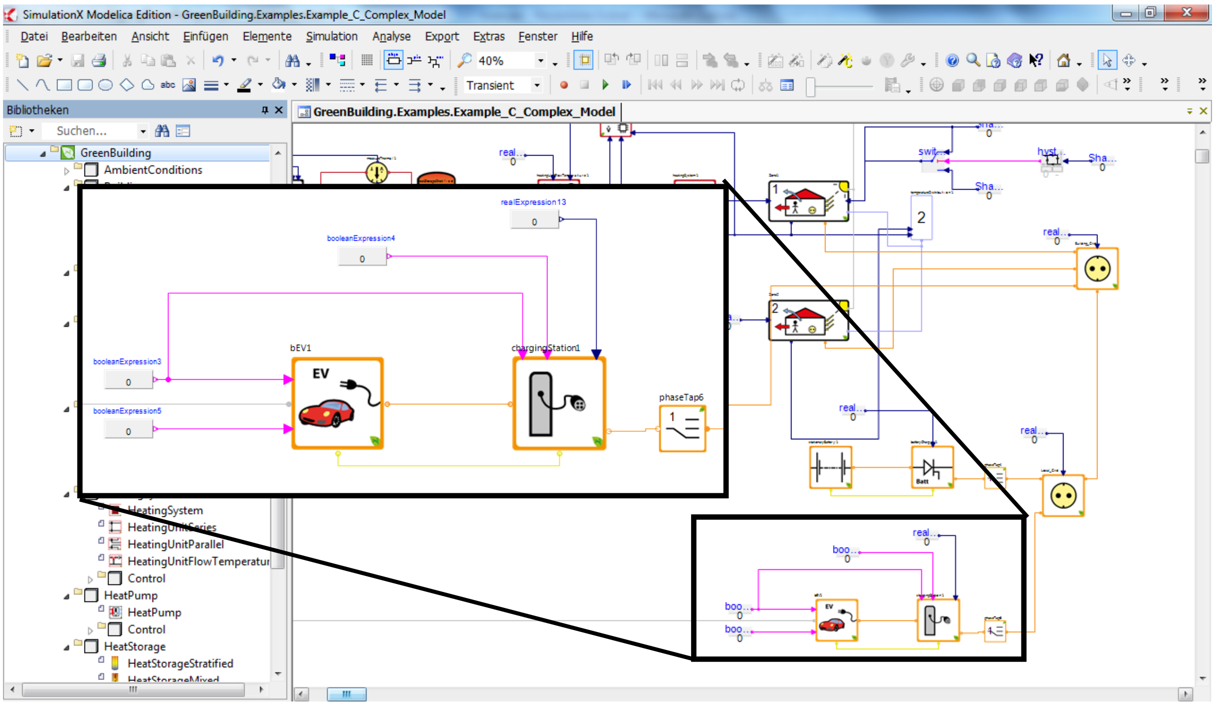

Fig. 3: Electric vehicle model as part of a complete 'Green Building' energy system model

Figure 3 shows that vehicles, either with conventional internal combustion engine, hybrid-electric or fully-electrified powertrain, are modelled as an equal part of a complete building energy system model. As presented before, vehicle model needs only two inputs representing the usage scenario of each vehicle. One input defines if vehicle is presented at the charging station (i.e. vehicle can be recharged) and if vehicle is driving when it is absent. Energy demand of vehicle is defined by constant parameters representing average electrical power during driving cycle (and fuel power demand in case of a hybrid powertrain).

These values are calculated in pre-processing using previously described vehicle powertrain simulation systems. That way, driving cycle simulations with low time constants are done independently from building simulations. This approach avoids stiff differential-algebraic equation systems and provides fast simulation runs for building energy system simulation.

The physical vehicle model (c.f. modelling paradigms) only consists of a medium-accurate battery model which is used to define state of charge of vehicle battery when vehicle returns to charging station.

Because powertrain behaviour is represented by constant average power demand values, transient building simulation needs two time-transient signals defining vehicle's presence and driving condition with Boolean states. Such vehicle usage scenarios are defined using an external program, named 'RouteSteward'.

EA Systems developed this program to automatically create these input data sets using an adequate and easy-to-use interface (fig. 4).

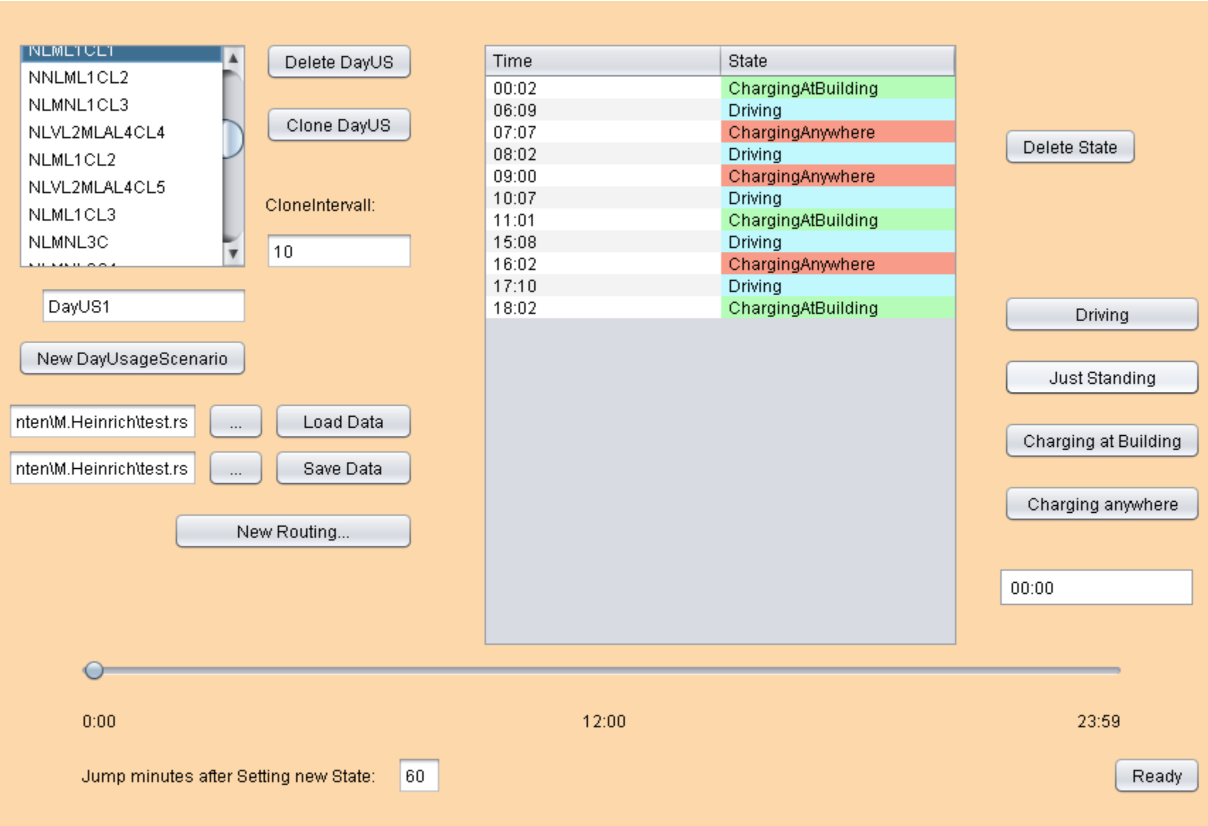

Fig. 4: Operator interface of Program 'RouteSteward'

In case of an office building with different vehicles and powertrain types in a vehicle fleet these work steps have to be repeated until all required input data sets and powertrain parameters have been calculated in pre-processing.

EXAMPLARY SIMULATION RESULTS FOR AN OFFICE BUILDING

Initial assumptions, model and scenario definitions

This paper shall exemplarily show the usage of presented framework to simulate and evaluate energy system behaviour of a building combined with a partly-electrified vehicle fleet. Because of nearest field of application an inner-city office building with a fleet with up to ten electric vehicles was chosen as a representative scenario.

The exemplary office building shall be located in the mid of Germany. It consists of five storeys with an overall net floor space of about 1.500 m^2. A standard office building load profile with about 50 kWh/m^{2}a electrical energy demand represents overall electrical energy consumption. As an academic example, heating system was modelled using a monovalent working combined heat and power unit with about 40 kW heat power output and an adequate heat storage.

All these definitions have to be made before the actual evaluation work to represent energy consumption and energy production of the building itself. This is necessary because building energy system shall provide energy not only for the vehicle fleet but also for the whole building (c.f. electrical energy consumption).

The actual example under consideration shall solve the question which size of a stationary battery is needed to optimize the own consumption of renewably produced energy in combination with different sizes and usage scenarios of an e-Vehicle fleet as well as a photovoltaic system with about 8.5 kWp installed power.

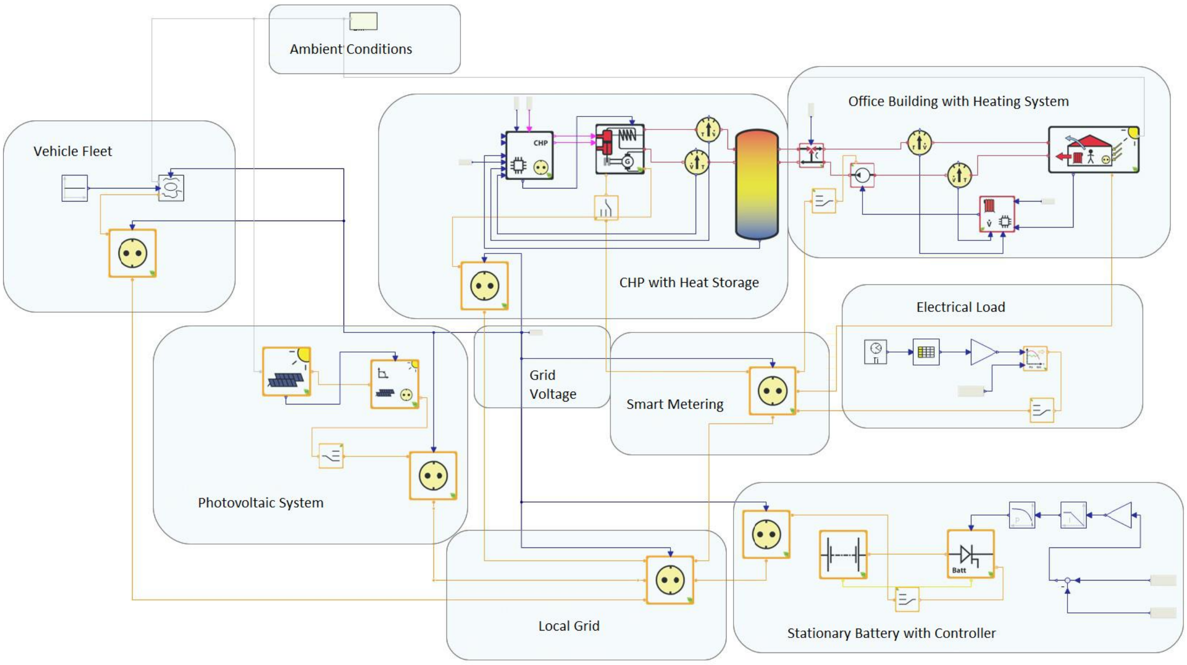

Fig. 5: Building energy system model with CHP, photovoltaic, battery and vehicle fleet

The vehicle fleet in figure 5 consist of maximum ten e-Vehicles with an average daily route of about 90 km. Number of vehicles is varied during optimization process. Although, usage scenario (c.f. presence at charging station and driving times) stays the same for each vehicle in different simulation runs usage scenarios can vary between two different types:

1. Vehicles can only be recharged during night after the end of work – over-night-charging
2. Vehicles return to charging station at noon and can be recharged at daytime – during-day-charging

Time	State
00:00	ChargingAtBuilding
07:00	Driving
10:00	Standing
16:00	ChargingAtBuilding

Time	State
00:00	ChargingAtBuilding
08:00	Driving
09:00	ChargingAtBuilding
10:00	Driving
11:00	Standing
11:40	ChargingAtBuilding
15:00	Driving
16:00	Standing
18:00	ChargingAtBuilding

Fig. 6: Usage scenarios for over-night-charging (left - 1) and during-day-charging (right - 2)

In case of over-night-charging all vehicles stay at the office building over the night. From 07:00 a.m. each vehicle is used by one employee for about three hours. Then, vehicles return to office building at 10.00 a.m. However, charging is forbidden in the middle of the day by energy management system because all renewably produced energy is needed to fulfil office's electrical energy demand. In the afternoon (16.00 p.m.), employees go home and charging can be started.

Second usage scenario describes an office building with a reduced electrical energy demand or an oversized renewable energy system (e.g. photovoltaic). That energy management allows vehicle charging during day. In this case, vehicles stay at office building as well. But from 08:00 a.m. till 09.00 a.m. vehicles are used first time of the day. After a short trip all vehicles return to office and can be charged for one hour. The same procedure happens before lunch. At 11.00 a.m. all vehicles return again. However, energy management detects high electrical energy demand before noon, recharging is forbidden for a short time period (e.g. because of meal preparation in canteen). Around noon vehicles can be recharged again to use available electrical energy by photovoltaic system. In the late afternoon vehicles are used again for about one hour. At the end of the working day all vehicles return to office again and can be recharged during the whole night.
In opposite to usage scenarios vehicle energy consumption is always pre-calculated using one representative driving cycle. Therefore, input data of ftp 75 driving cycle is used during pre-processing. Finally, to reduce simulation time different relevant reference days are analysed instead of whole years in this exemplary scenario:

1. Sunny winter day (Ws)
2. Sunny summer day (Ss)
3. Overcast summer day (So)

Some exemplary simulation results

Focus of further analyses are overall electrical energy consumption from grid and energy fed into local grid. Furthermore, all results are discussed with respect to influences of building energy system configuration (mainly stationary battery size) on analysed vehicle fleet. Thereby, three different battery sizes are used within simulation studies – 0 kWh, 25 kWh and 50 kWh.

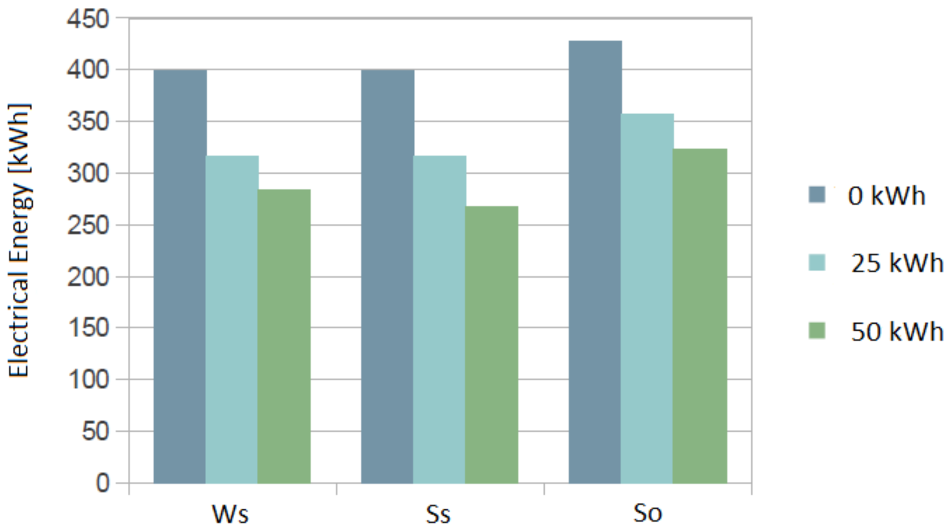

Fig. 7: Difference between overall electrical energy consumption and grid-feeding depending on battery capacity with eight vehicles and during-day-charging scenario

Figure 7 shows that the installation of comparatively low battery sizes can reduce electrical energy balance of such an office building including a vehicle fleet. This mainly depends on high renewable energy production by photovoltaic system during noon and comparatively low

electrical energy consumption during that time period. The amount of energy consumption reduction differs between a sunny and an overcast day because of lower renewable electrical energy production. In this case, influences of battery size stay the same.
Furthermore diagram in figure 7 shows that winter and summer energy balance are almost the same. This is caused by different amount of electrical energy production of CHP and photovoltaic system. Reductions of photovoltaic gains are compensated by heating via CHP during day time in winter.
Following exemplary analyses refer to renewable energy share of vehicles' electrical energy consumption depending on stationary battery size and analysed reference day.

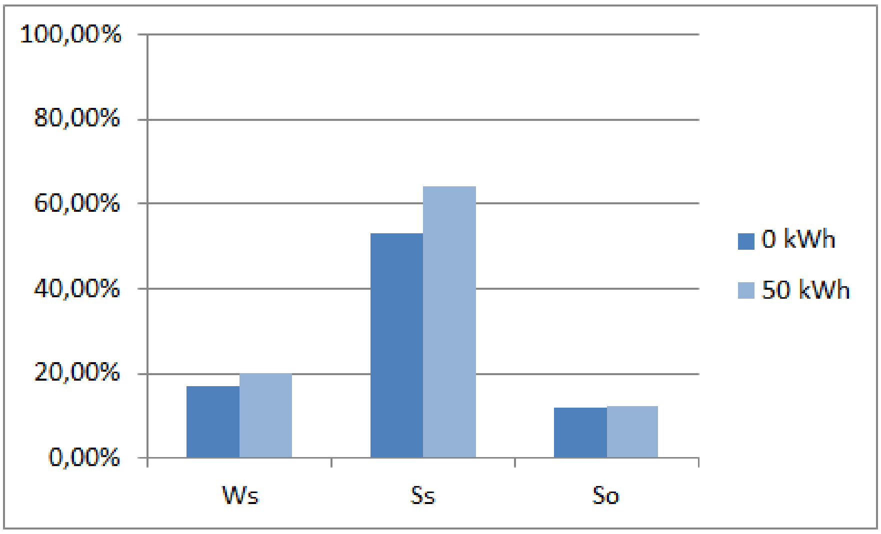

Fig. 8: Renewable energy share of electricity consumption of a fleet with 4 vehicles depending on stationary battery size

Depending on available renewable energy (increased energy gains at sunny summer day (Ss) by photovoltaic system) a remarkable amount of vehicles' energy consumption can be provided by locally produced renewable energy (up to 50 %). Figure 8 shows results of the analysed academic example for vehicle fleet with four cars. Furthermore, results show that integration of stationary batteries in building energy systems increases the renewable energy usage in a significant way. In this case, amount of renewable energy for mobility purposes can be increased up to 15% (sunny summer day).
This simple example shows the increasing importance of local energy storages, especially regarding gradually decreasing salaries for grid-feeding. However, defining right sizes of storage systems for specific buildings (e.g. offices) and usage scenarios (e.g. with a vehicle fleet) needs adequate simulation analyses because static approaches cannot meet requirements of state-specific system control and capacity availability.
Finally, size of vehicle fleet and its influences on overall renewable energy usage in the office building shall be depicted. Therefore, figure 9 shows the amount of fed electrical energy depending on analysed reference day as well as three different vehicle fleet sizes. In this case a stationary battery with a capacity of 50 kWh was used.
First of all, it is remarkable that electrical energy is fed into grid even at a cloudy summer or sunny winter day. That shows that the installed photovoltaic and CHP system might be slightly over-sized. However, regarding this academic example, building energy system dimensioning has not been given special emphasis.
Furthermore, significant reductions of grid-feeding regarding an increased size of vehicle fleet can be seen in figure 9 as well. That shows the importance of upcoming e-Mobility as additionally available electrical energy storage capacity (c.f. pump storage stations).

Fig. 9: Overall electrical energy grid-feeding at analysed reference days depending on vehicle fleet size

From grid's point of view a major number of vehicles with electrified powertrain and plug-in interface will represent a significant electrical energy storage capacity. That way, peak loads coming from short-time electrical energy consumption peaks or high renewable electrical energy production by big solar systems in times of lower energy demand (e.g. noon in summer holydays) could be buffered. However, further technical solutions, e.g. battery aging and charging infrastructure, have to be engineered. Therefore, economical and political framework conditions have to be evaluated and adapted as well.

SUMMARY AND CONCLUSION

This paper presents practices to analyse energy consumption as well as renewable energy usage of vehicle fleets in combination with building energy supply based on EA Systems' 'Green Building' simulation package. Therefore, the chosen approach used to combine highly dynamic vehicle with building energy system simulation is depicted.
Based on an academic example of an office building with a connected e-Vehicle fleet some interesting simulation results are shown. Furthermore, these results are analysed regarding reasonableness of technical measures as well as further economical and technical aspects.

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