LOCAL AND GLOBAL SIMULATION OF SOLARKIOSKS

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I. INTRODUCTION AND RESEARCH OBJECTIVES

More than 80 % of the people without access to electricity live in rural regions of developing countries [1]. The SOLARKIOSK [2] is designed to empower these people to create an autonomous business based on PV energy. The product has been successfully rolled out in Ethiopia in 2012, where seven SOLARKIOSKs have been installed and are running since July 2012 (figure 1, 2).

Fig. 1 - First SOLARKIOSK at Lake Langano, Ethiopia [2]

Fig. 2 - First SOLARKIOSK at Lake Langano, Ethiopia at night [2]

Five more SOLARKIOSKs have been installed in Kenya in spring 2013. Simulations have been carried out to analyze detailed questions of the energy system, but also to calculate the market potential of the SOLARKIOSK on a global scale.

II. APPROACH AND METHODS

Due to the different requirements of the simulation outputs we have made two different approaches to simulate the SOLARKIOSK: On the local scale INSEL® [3] and for the global analysis MATLAB® has been used.

Table 1 - Comparison INSEL and MATLAB

Program	INSEL	MATLAB
Method	Detailed modeling of the SOLARKIOSK energy system	Automatic cost optimized sizing model of the SOLARKIOSK
Aim	System design evaluation	Worldwide pre-feasibility study

For the local simulation with INSEL a demand side management (DSM) and a fridge model have been implemented and tested in INSEL.

Demand side management

This model has been programmed to calculate the load in dependency of the input parameters in Fig. 3 for given components. The energy system of the SOLARKIOSK has to supply the energy for internal loads, like lamps, fridge, radio and for external loads like charging mobile phones.

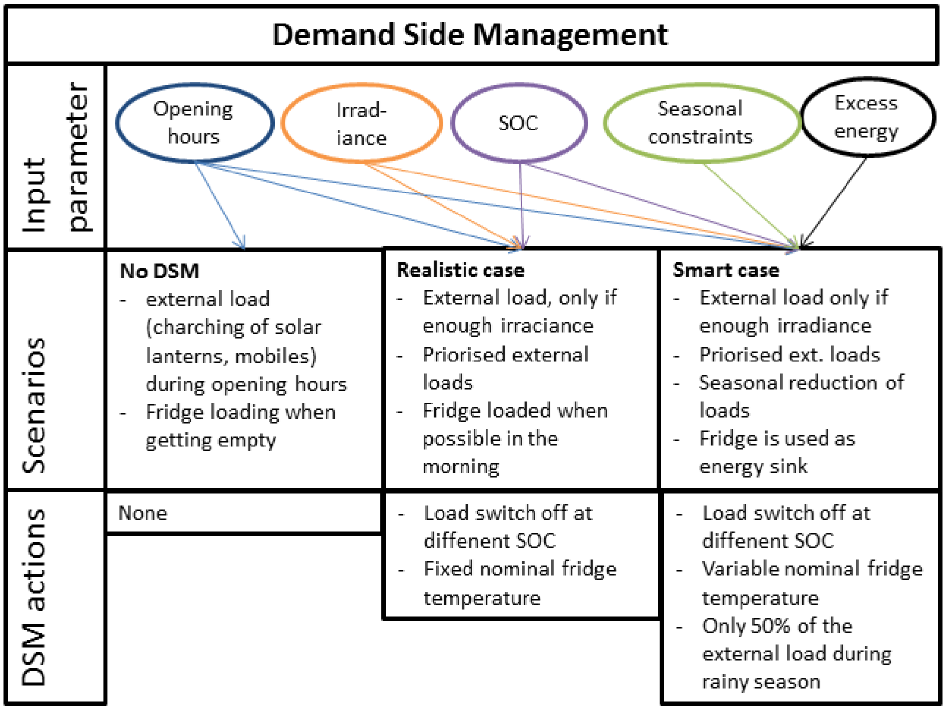
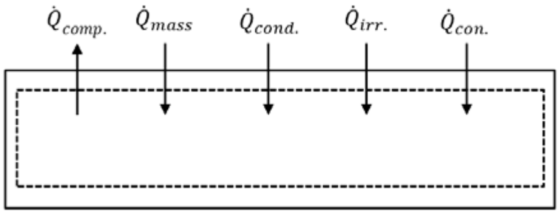


Fig. 3 – Block schematic of the demand side management

Fridge

Theoretically every fridge can be described with the energy balance below.

$$\frac{dU}{dt} = \dot{Q}_{comp.} + \dot{Q}_{mass} + \dot{Q}_{cond.}(+\dot{Q}_{irr.} + \dot{Q}_{con.}) \qquad (1)$$



$\frac{dU}{dt}$ ... *change of intrinsic energy*

$\dot{Q}_{comp.}$... *heat transport of the compressor*

$\dot{Q}_{mass}$... *heat transport due to the mass in and output*

$\dot{Q}_{cond.}$...*heat transport due to conductivity*

$\dot{Q}_{irr.}$... *heat transport due to irradiance*

$\dot{Q}_{con.}$... *heat transport due to convection*

Fig. 4 – Theoretical fridge model

The heat transport caused by irradiance and convection have been neglected. After the development of the analytical model the parameters for calculation of the coefficient of performance *COP* and the power *P* are based on measurements on the fridge PF 166 of Steca [4]. Our modell has derived on three test series with different temperature spreads $\Delta\vartheta$ between the internal fridge temperature the nominal temperature ϑ_{nom}. Furthermore different scenarios on loading the fridge with water bottles have been measured. Based on this data a model has been created. The in- and output parameters can be taken from table 2.

Table 2 - Parameters of the fridge model

Input parameter		Output parameter	
Ambient temperature	ϑ_{amb}	Mass inside fridge	m_{fridge}
Nominal temperature	ϑ_{nom}	Power	P_{tot}
Temperature of inserted mass	ϑ_{m}	Temperature inside the fridge	$\vartheta_{\mathrm{fridge}}$
Mass input	m_{in}		
Mass output	m_{out}		

The following procedure is only valid for 40°C > ϑ_{amb} > 12°C and the PF 166 of Steca. The empirical model is based on 5 s values. At the beginning of each simulation step the mass m_{fridge} has to be calculated. Values that are marked with an ´ refer to the anticipated simulation step or are initial values.

$$m_{\mathrm{fridge}} = m'_{\mathrm{fridge}} + m_{\mathrm{in}} - m_{\mathrm{out}} \qquad (2)$$

Through specific heat capacity c of the cooled material the heat capacity of the material can be calculated.

$$C = m_{\mathrm{fridge}} * c \qquad (3)$$

The empirical formula for the coefficient of performance *COP* can be calculated via ϑ_{nom} and $\vartheta_{\mathrm{amb.}}$

$$COP = 0.0024 * (\vartheta_{\mathrm{amb}} - \vartheta_{\mathrm{nom}})^2 - 0.1771 * (\vartheta_{\mathrm{amb}} - \vartheta_{\mathrm{nom}}) + 4.9609 \qquad (4)$$

The temperature difference can be described as followed.

$$\Delta\vartheta = \vartheta_{mix} - \vartheta_{nom} \qquad (5)$$

For this the mixed temperature ϑ_{mix} inside the fridge for (partly) exchanging masses is needed.

$$\vartheta_{\mathrm{mix}} = \frac{(m'_{\mathrm{fridge}} - m_{\mathrm{out}}) * \vartheta_{\mathrm{fridge}} + m_{\mathrm{in}} * \vartheta_{\mathrm{m}}}{m_{\mathrm{fridge}}} \qquad (6)$$

For the calculation of the ϑ_{fridge} parameters from the former simulation steps are needed.

$$\vartheta_{\mathrm{fridge}} = \vartheta'_{\mathrm{mix}} * \frac{5 * \Delta P'_{\mathrm{cur}} * COP'}{3600 * C'} \qquad (7)$$

The current power ΔP_{cur} has to be calculated using three different formulas for the power depending on ϑ_{amb} (25°C, 30°C, 35°C). For each case the fridge needs more power if the temperature difference $\Delta\vartheta$ between the current mixed temperature inside the fridge ϑ_{mix} and the nominal temperature ϑ_{nom} gets wider.

$$for\ \vartheta_{amb} = 25°\mathrm{C};\ P_{25}(\Delta\vartheta) = \begin{cases} 0; & \Delta\vartheta < 1.4\,K \\ 0.1076\,\Delta\vartheta^2 + 2.3143\,\Delta\vartheta - 2.2175; & 1.4\,K < \Delta\vartheta < 19.2\,K \\ 100; & 19.2\,K < \Delta\vartheta \end{cases} \qquad (8)$$

$$for\ \vartheta_{amb} = 30°\mathrm{C};\ P_{30}(\Delta\vartheta) = \begin{cases} 0; & \Delta\vartheta < 1.4\,K \\ 0.1805\,\Delta\vartheta^2 + 1.7209\,\Delta\vartheta + 0.3334; & 1.4\,K < \Delta\vartheta < 19.2\,K \\ 100; & 19.2\,K < \Delta\vartheta \end{cases} \qquad (9)$$

$$for\ \vartheta_{amb} = 35°\mathrm{C};\ P_{35}(\Delta\vartheta) = \begin{cases} 0; & \Delta\vartheta < 1.4\,K \\ 0.1842\,\Delta\vartheta^2 + 2.9288\,\Delta\vartheta - 1.9909; & 1.4\,K < \Delta\vartheta \le 15.9\,K \\ 1.3131\,\Delta\vartheta + 70.269; & 15.9\,K < \Delta\vartheta \le 22.6\,K \\ 100; & 22.6\,K < \Delta\vartheta \end{cases} \qquad (10)$$

$$for\ \vartheta_{amb} < 25°\mathrm{C};\ \mathrm{use}\ P_{25}(\Delta\vartheta);\ and\ for\ \vartheta_{amb} < 35°\mathrm{C};\ \mathrm{use}\ P_{35}(\Delta\vartheta) \qquad (11)$$

If the ϑ_{amb} lies between temperatures mentioned above, the weighted average for the power $\Delta P_{curr,40}$ has to be calculated like for example an ambient temperature between 25°C and 30°C (likewise for 30°C < ϑ_{amb} <35°C:

$$\Delta P_{curr,40} = \frac{(\vartheta_{\mathrm{amb}} - 25) * P_{25}}{5} + \frac{(30 - \vartheta_{\mathrm{amb}}) * P_{30}}{5} \qquad (12)$$

Furthermore the power of the fridge is highly dependent on the mass it cools ($P \sim m$). As all the parameters were measured for a mass of 40 kg the current power ΔP_{curr} has to be calculated using the following simple formula:

$$\frac{\Delta P_{\mathrm{curr}}}{\Delta P_{curr,40}} = \frac{m_{\mathrm{curr}}}{40\ \mathrm{kg}}, \text{ if } \Delta P_{curr} > 100\ \mathrm{W}, \text{ than } \Delta P_{curr} := 100\ \mathrm{W} \text{ (maximum power of the compressor)} \qquad (13)$$

The power that is needed to compensate the losses cause by heat conduction P_{con}, for the case $\vartheta_{amb} < \vartheta_{nom}$ are given by:

$$P_{\mathrm{con}} = 0.0088 * (\vartheta_{\mathrm{amb}} - \vartheta_{\mathrm{nom}})^2 - 0.031 * (\vartheta_{\mathrm{amb}} - \vartheta_{\mathrm{nom}}) + 0.9517 \qquad (14)$$

The total power P_{tot} for a given time step is defined as,

$$P_{\mathrm{tot}} = P_{\mathrm{con}} + \Delta P_{\mathrm{curr}} \qquad (15)$$

These formulas were implemented in INSEL to calculate the total power of the fridge very precisely by manipulating the nominal temperature making it possible to evaluate the potential of the fridge as energy sink.

MATLAB has been used to compare the cost effectiveness of the different scenarios, by calculating the levelized cost of electricity (LCOE) for every configuration of the energy system worldwide.

Table 3 – *Parameters for the LCOE calculation*

	PV system	**Battery**	**Kiosk**
capex	1.04 €/Wp	0.17 €/Wh	6.25 €/Wp
opex	0.0156 €/Wp*a	-	-
lifetime	20 a	8 a	20 a
WACC	6 %	6 %	6 %

$$LCOE = \frac{capex \cdot crf + opex}{E_{cons}} \qquad (16)$$

$$crf = \frac{WACC \cdot (1 + WACC)^n}{(1 + WACC)^n - 1} \qquad (17)$$

*capex…*capital expenditures
crf…capital recovery factor
E_{cons}*…annual consumed energy*
opex…annual operation and maintenance expenditures
WACC…weighted average cost of capital
n…lifetime

The load curve for the economic evaluation has been based on the load curve of the realistic scenario of figure 3. To match the best LCOE for each location the battery and the PV generator has been sized individually in given steps according to the modularity of the SOLARKIOSK. It has been assumed that the alternative to generate power in remote areas is done with diesel generators. Therefore the LCOE of the stand-alone PV systems of the SOLARKIOSK have been compared to the LCOE of a diesel generator which depend highly on the costs of the diesel. To calculate diesel price for every location, national prices have been identified. An extra factor has been added to reflect the transport costs, so that in remote areas the diesel price rises compared to the capital [5]. The model for the worldwide economical evaluation has been based on the work of Szabó et al. [6].

III. RESULTS

Figure 5 shows a simulation of the load and the state of charge of the battery, for the SOLARKIOSK built at Lake Langano for a full year. In contrast to the scenario “no DSM” and the “realistic case” (see figure 5), in the plotted smart case the fridge was used as an energy sink to reduce the excess energy by applying a variable nominal temperature between 3°C and 12°C. During the nighttime the nominal temperature inside the fridge is raised to 12°C. The power of the fridge is calculated additionally to the other loads and is plotted in black. It can be seen that the power of the fridge rises when the SOC (red curve) rises and when the battery gets empty, the fridge consumes less in order to make the battery capacity last longer. Moreover the other internal and external loads (green curve) are switched on and off according to the irradiance. The two intervals marked with the number “2” indicate the rainy season. As described in figure 5 during these days only 50 % of the external loads are covered. Comparing the different scenarios it has been shown, that using a smart DSM, the LCOE of the energy system of the SOLARKIOSK have been reduced by 57 % compared to a scenario without DSM [7]. This effect can be explained by the reduction of the installed battery capacity to cover the same load as in scenario “no DSM” by shifting the load.

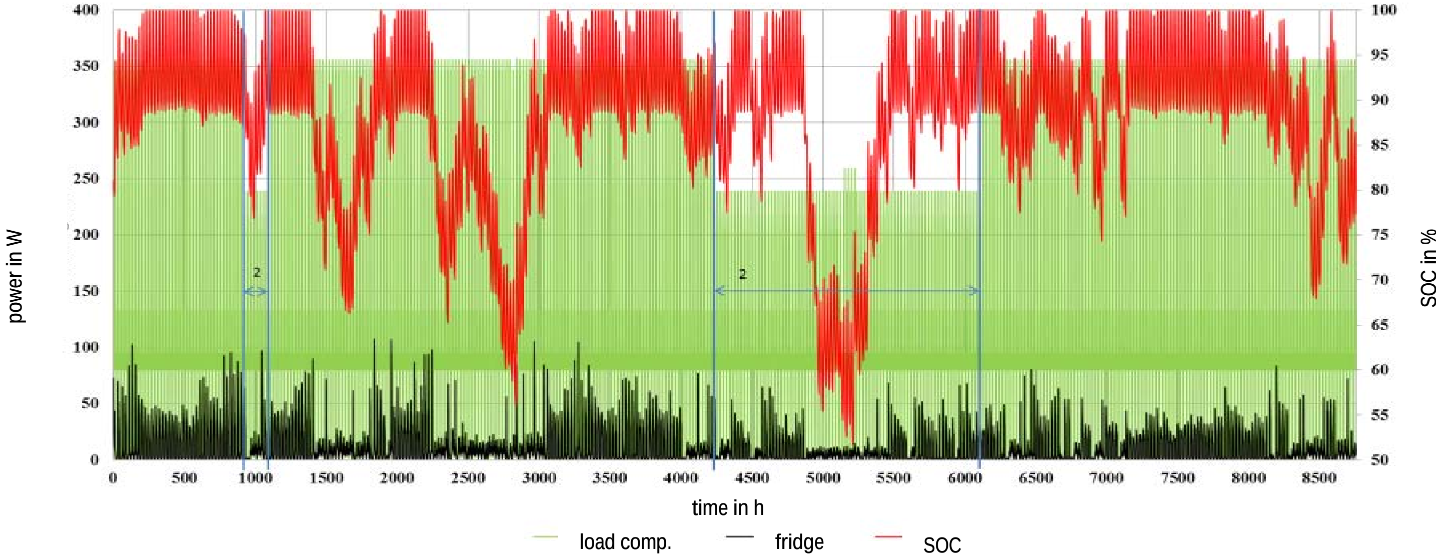


Fig. 5 - Simulation of the loads and the SOC of the SOLARKIOSK at Lake Langano for the year 1995 for the scenario DSM 4

Figure 6 shows the cost advantage of PV-battery systems as it is used in the SOLARKIOSK vs. diesel systems in a broader perspective. It can be seen, that increasing distance to large trade routes leads to high transport costs for diesel, thus making the PV systems costs competitive. Regions like the Amazonas, the Himalayas and the Sahara are particularly striking. On the other hand oil-producing countries like Saudi Arabia, Algeria or Angola are really difficult regions for the SOLARKIOSK to succeed economically, because of the relatively low price for diesel. It can be summed up, that in large areas of Africa a cost advantage or only a small cost disadvantage of the stand-alone PV system of the SOLARKIOSK vs. the energy costs of a diesel generator can be seen. Considering that the price of diesel is based on data from 2010 and has tended to increase in recent years, while the cost of PV components are still declining there is still some potential which is not shown at figure 6.

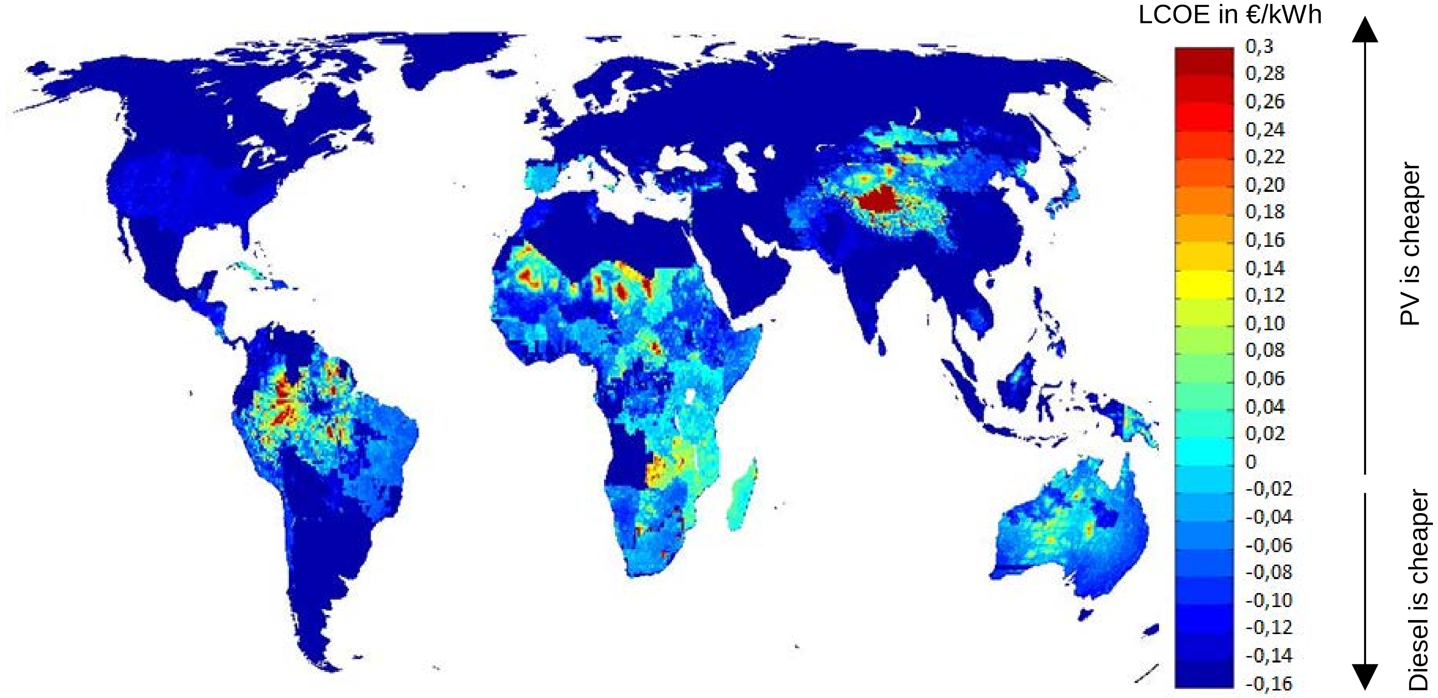


Fig. 6 – *Cost advantage of PV-battery systems vs. diesel generator systems*

IV. CONCLUSION/ OUTLOOK

It is shown, that different methods of simulating the SOLARKIOSK on local and on a global scale lead to interesting results. For a detailed analysis of the SOLARKIOSK on a local scale a fridge model has been added to a demand side management resulting in a highly effective way to reduce LCOE drastically by using the fridge as energy sink. A LCOE reduction of up to 57 % has been calculated for a SOLARKIOSK in Ethiopia. The simulation model of the fridge has been described in detail so that it can be used for further projects. The global analysis has shown that the energy systems used in the SOLARKIOSK are highly competitive to diesel generator systems in many countries in the world.

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