DEMAND SIDE AND BATTERY MANAGEMENT IN SOLARKIOSKS – SIMULATION AND OPERATING EXPERIENCE

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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 main business will be done by charging solar lanterns, mobile phones and external batteries, but also cooling services can be provided. It is especially designed to be transportable far off-grid and to be modular, so in case of a successful business an internet café or water purification can be added. The worldwide PV-based off-grid market potential is estimated to be about 70 GW [3]. For economic reasons and due to the high solar irradiation Ethiopia is chosen for the first implementation of the SOLARKIOSK [4].

II. APPROACH, METHODS AND POTENTIAL ESTIMATION

Knowing that the biggest problem in economic stand-alone PV systems is the excess energy, our aim is to reduce it to a minimum using an energy effective demand side management (DSM). Following a heuristic approach by measuring different cases in a climate chamber and respecting the physical basics of the cooling mechanism a simulation model for the fridge could be derived. The fridge has been loaded with different amounts of water bottles and the ambient temperatures have been varied, meanwhile the voltage and the current of the fridge have been measured to cool the water to a nominal temperature. By fitting the power curve with the method of the least squares, formulas for the coefficient of performance (*COP*), the power (*P*) and the temperature inside the fridge (θ_{in}) depending on the ambient temperature (θ_{amb}), the cooled mass (*m*) and the nominal temperature inside the fridge (θ_{nom}) have been developed. This led to a better understanding of the temperature dependence of the power of the fridge. Creating a tool that calculates a temperature and business model depending load curve, five load curves have been calculated. For all scenarios the following items need to run or be charged within the kiosk.

Table 1 – *Items within the SOLARKIOSK*

	LED strips	LED spots	Fridge	Radio/ Music	Mobile phone	Solar lantern
Power in W	12	2.5	40..100	40	3.4	5
Pieces	2	2	1	1	60/d	100/d

- ***No DSM**: charging of mobiles and solar lantern during the opening hours (7 a.m. and 12 p.m); frige is constantly loaded when getting empty*
- ***DSM 1**: charging of mobiles and solar lantern only during daytime, fridge is fully loaded between 10 and 11 a.m. and constantly loaded when getting empty during daytime*
- ***DSM 2**: like DSM 1 but during the rainy seasos (day 40 to day 44 and day 177 to day 254) only 50 % of the mobiles and lanterns are loaded*
- ***DSM 3**: like DSM 2 and the excess energy is used to purify water*
- ***DSM 4**: like DSM 2 and the excess energy is used to cool down the fridge at daytime to minimize energy consumption at nighthours*

Using the programming language INSEL [5], the electric and the water purification system, based on the SuMeWa | SYSTEM by AUTARCON [6] have been modeled. The graphical interface of INSEL has been used to simulate the electrical system using the functional blocks integrated [7] but some items, as the fridge and the load generation have been programmed in Fortran and added to INSEL. To provide constituency to other projects at the Reiner Lemoine Institut the internal weather data of INSEL have not been used. The used weather data covering a period of 22 years (1984 to 2005) are provided by NASA and processed by the DLR [8].

Unlike other stand-alone solutions simulated with INSEL [9] the SOLARKIOSK has been modeled as a 100 % renewable energy solution with the focus to integrate and control the load as much as possible into the energy system. Therefore a user based and automatic DSM has been implemented. By training the SOLARKIOSK operator a user based DSM like charging the fridge between 10 and 11 a.m. has been realized. In addition an automatic DSM has been developed using irradiance coupled switches and the internal control of the solar power electronics to charge mobile phones and lanterns only during daytime, let the internal lights of the kiosk only run at nighttime and drop off 50 % of the lanterns and mobile phones at the rainy season. Two other functions have been added to the automatic DSM: A water purification system and an intelligent fridge. Both of them are designed to reduce the excess energy, one system by purifying and pumping water the other by cooling down in time of high irradiation and switching off at nighttime.

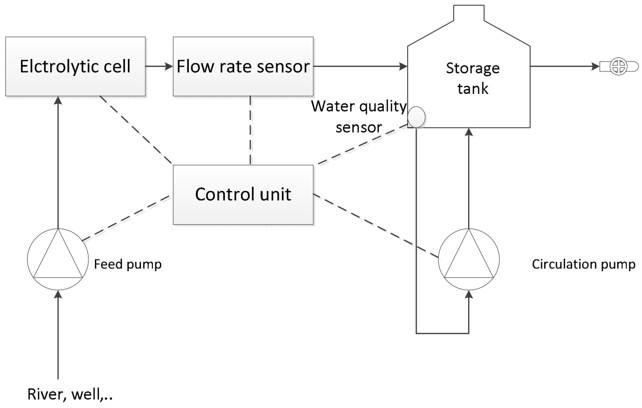

Fig. 1 – *Block diagram of the SuMeWa | SYSTEM of Autarcon*

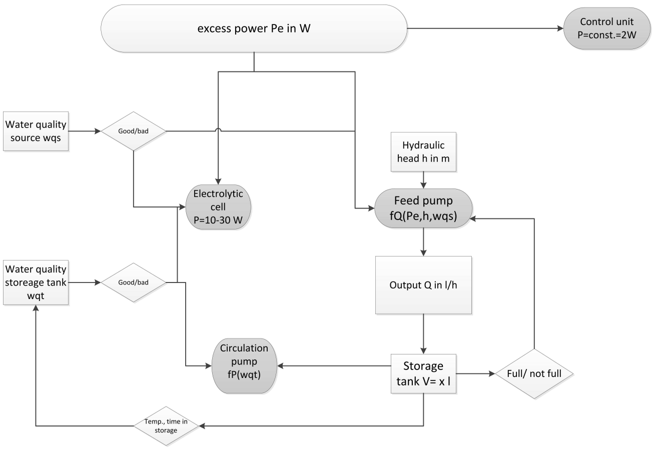

Fig. 2 – *Structure chart of the SuMeWa | SYSTEM model implemented in INSEL*

The water purification system SuMeWa (fig. 1) that has been implemented in INSEL is an almost maintenance free system able to produce chloride via an electrolytic process. As it can be seen in fig. 2 the amount of energy used by the system to purify water depends highly on the water quality of the source from which the water is pumped and the hydraulic head. Other factors as the dwell time of the water in the storage tank also influence the energy efficacy of every m³ of purified water, as it has to be purified again if the dwell time is too long. We have calculated an electrical energetic potential of 1.2 kWh (34 % of the daily load) to fill a 1600 liter tank with river water at a flow rate of 270 l/h. For this worst case scenario a bad water quality and a hydraulic head of 60 m. has been assumed.

By modeling the fridge three main factors which influence the power of the fridge have been identified: the nominal temperature inside the fridge, the mass which is filled in and the temperature of this mass. The nominal temperature can be regulated from 2℃ to 12℃ in 1℃ steps, this has the effect that the nominal temperature can be decreased for example at daytime and risen at nighttime. This process has been developed to be part of the automatic DSM and is therefore controlled automatically by the system. The scenario DSM4 has been simulated using this function. For all other variations, except the no DSM scenario we have assumed, that the SOLARKIOSK operator fully charges the fridge in the morning when the sun is already providing enough energy to charge the battery and cool the water as described above.

To estimate the electrical potential of the fridge as an energy sink the energy consumption of the fridge has been calculated to cool 72 kg of water (max. capacity) for a minimal and a maximal ambient temperature of $\theta_{amb,min}$ =15℃ and $\theta_{amb,max}$ =23℃ (coldest and warmest day of the year for Lake Langano, Ethiopia) to a nominal temperature of 3℃ and 12℃ during 24 hours. As it can be seen in fig. 3 the energy potential at this location is between 260 Wh/d and 400 Wh/d. Based on the total daily consumption of 3.5 kWh the potential of 7% to 11% of the daily load might be shifted into the sunshine hours were the excess energy can be used to cool down the fridge to 3℃ and raise the ambient temperature of the fridge at night hours to 12℃.

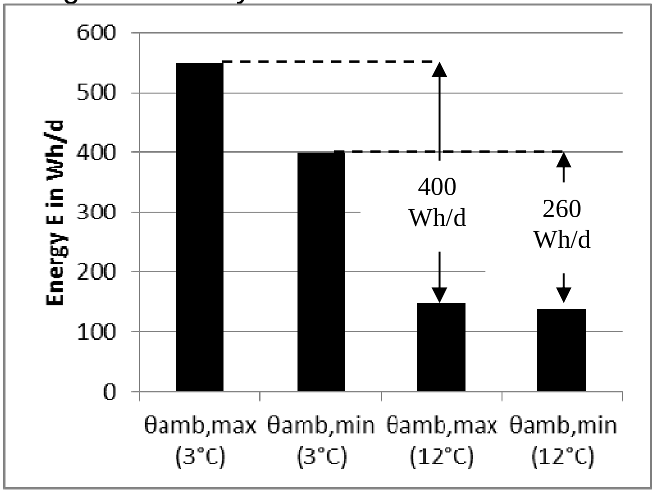

Fig. 3 – *Energy consumption of the fridge for the warmest and coldest day at Lake Langano*

To adjust the simulation of the SOLARKIOSK to the measured data a 3 month data period has been compared to the simulated data. As the focus lies on the battery characteristics we have compared the different state of charges (SOC). The simulation of the user based demand side management as well as the automatic DSM has been performed for Lake Langano, Ethiopia, the location of the first SOLARKIOSK implemented in Africa where no demand side management has been implemented yet.

Fig. 4 – *First SOLARKIOSK at Lake Langano, Ethiopia [2]*

Fig. 5 – *First SOLARKIOSK at Lake Langano, Ethiopia at night [2]*

To compare the cost effectiveness of the different scenarios the levelized cost of electricity (LCOE) for every configuration of the energy system has been calculated according to equation 1 and 2.

$$\mathrm{LCOE} = \frac{capex \bullet crf + opex}{E_{cons}}$$

$$crf = \frac{WACC \bullet (1 + WACC)^n}{(1 + WACC)^n - 1}$$

Equation 1 and 2: LCOE: Levelized cost of electricity. Abbreviations stand for: capital expenditures (*capex*), annual operation and maintenance expenditures (*opex*), annual consumed energy (E_{cons}), capital recovery factor (*crf*), weighted average costs of capital (*WACC*) and lifetime (*n*).

The economical evaluation has been done for the location mentioned above and also worldwide. It has been assumed that the alternative to generate power in remote areas is done with diesel generators. Therefore the levelized cost of electricity 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 [10]. The model for the worldwide economical evaluation has been based on the work of Szabó et al. [15].

III. RESULTS

Figure 6 shows the power input of the fridge for 96 hours in 5 sec. steps. The blue line shows the measured power of the fridge that was loaded and unloaded with water bottles like in a running kiosk. Furthermore the fridge was put in a climate chamber running on the climate of Lake Langano, Ethiopia. Using the same parameters the red graph shows the power, as it has been simulated by the fridge model. The dotted line shows the cumulated energy of the real and the simulated fridge, thus giving a picture of the failure of the fridge model. It can be seen that for the first 45 hours when no additional cooling mass is inserted in the fridge, the model is very close to reality. But between hour 45 and 84 the energy consumption of the fridge is calculated too low. As a relative failure the simulation calculates 5 % less energy consumption during the 96 h test. Being the only temperature dependent load, the fridge model has been used to calculate the load curve for the different scenarios described above.

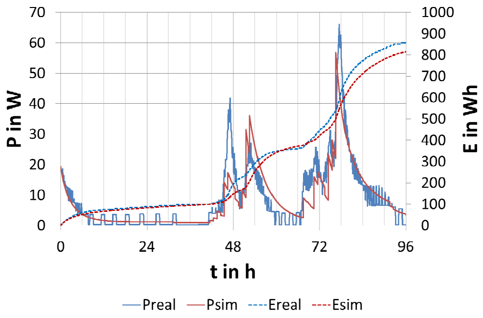

Fig. 6 – *96 h evaluation of the of the fridge model compared to a real scenario at Lake Langano*

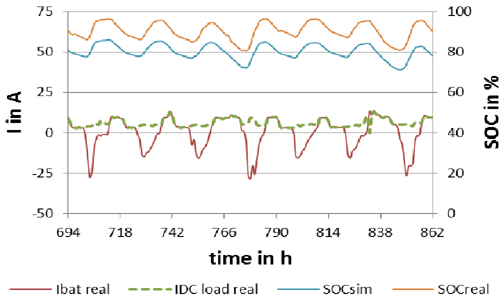

Fig. 7 – *Comparison of the state of charge (SOC) between the simulated values and the measured one from 25th to 31st of August;*

Evaluations of a 79 days measurement period of the SOLARKIOSK at Lake Langano have shown, that only 0.36% of the load has been used as alternating current (AC). This is due to the fact that the SOLARKIOSK operator is using mainly the internal loads of the kiosk and only a few external direct current (DC) loads. Therefore all the loads are calculated as DC loads and no conversion losses to AC are taken into account. The daily mean load for the measured period has been 1.752 kWh/d, which is approximately 50 % of the load that is assumed according to the business model presented in table 1. The main consumption caused by lights, radio and the fridge is during the night hours. Due to the better power to price ratio of DC systems the LCOE of table 2 is calculated with a DC stand-alone system [11]. Figure 7 shows an exemplary week of the measured period. The aim has been to evaluate the battery model used in INSEL, as the PV power is fixed by the kiosk dimensions and so the battery capacity depends directly on the load curve. The measured currents for the DC load (I_{DC} load real) and the current flowing in and out of the battery (I_{bat} real) are plotted. Negative values stand by definition for charging the battery, whereas positive values stand for discharging. It can be seen that the system is capable of charging the battery every day, caused by a great amount of excess energy due to the fact that the load is not as big as assumed when the system was dimensioned. Moreover the state of charges (SOC) of the INSEL battery model and the real SOC as a result of the power electronics in the kiosk are compared, revealing a mean deviation of 12 % caused by the conservative SOC calculation in the INSEL model. The deviation might be due to the standard battery model for lead acid batteries used in INSEL which is obviously more conservative than the real SOC calculated for the implemented OPzV lead acid batteries by the power electronics. As it can be seen in Figure 8 the electric system consists of 2 strings with 2 modules in series with a maximum power point (MPP) charge controller for each string and a 12 V-battery. The internal lights and the fridge run with 12V and the mobile phones and lanterns are either 5 V or 12 V. For the different DSM scenarios simulated in INSEL the minimal SOC is fixed to 50 %, and this, considering the conservative battery model, results in slightly higher battery capacities as it would be in reality. Moreover the hydraulic head for the water purification calculated in the scenario DSM3 is 60 m, the water quality is comparable to river water and the water storage volume is 1600 l.

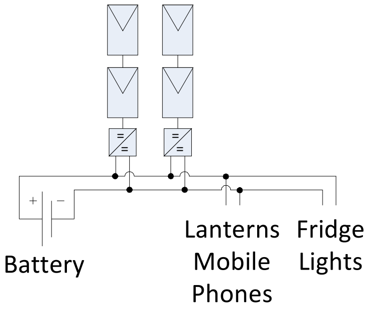

Fig. 8 – *Block diagram of the simulated system*

Table 2 – *Parameters for the LCOE calculation*

	PV system	**Battery**	**Kiosk**	**Water purification system**
capex	1.04 €/Wp	0.17 €/Wh	6.25 €/Wp	10 t€/unit
opex	0.0156 €/Wp*a	-	-	-
Lifetime	20 a	8 a	20 a	20 a
WAAC	6 %	6 %	6 %	6 %

Figure 9 shows a yearly simulation of the power of the load and the state of charge of the battery, for the SOLARKIOSK built at Lake Langano. In contrast to the scenario DSM3, in the plotted scenario DSM4 the fridge was used as an energy sink to reduce the excess energy as described above. This is reached by applying a variable nominal temperature between 3℃ and 12℃. During the nighttime the nominal temperature inside the fridge is raised to 12℃. 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 scenarios DSM 2,3 and 4 during these days only 50% of the external loads like the charging lanterns and mobile phones is offered. If this method hadn´t been applied the battery capacity would have dropped below 50% SOC and therefore it would have been necessary to design the battery bigger.

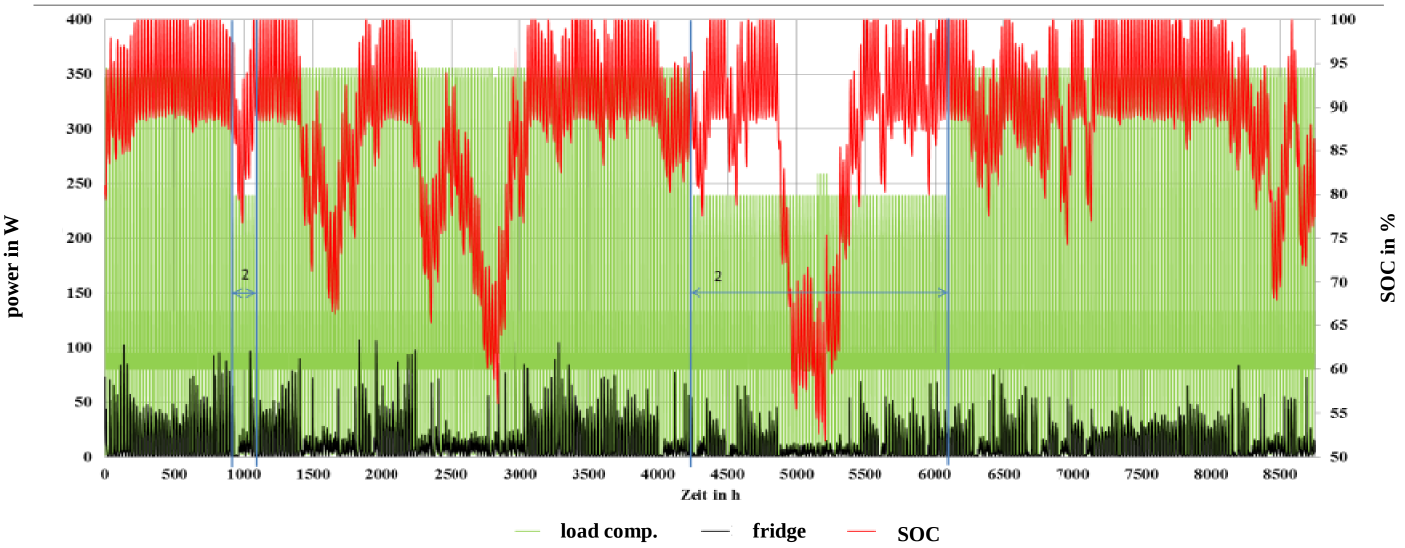

Fig. 9 – *Simulation of the loads and the SOC of the SOLARKIOSK at Lake Langano for the year 1995 for the scenario DSM 4*

The calculated system losses for the scenario without DSM of the SOLARKIOSK at Lake Langano are shown in figure 10. The battery efficiency (for Wh) [7] and the array soiling losses are values taken from the literature [12]. Converter efficiency losses and the losses due to missing the MPP have been simulated with INSEL according to the specifications of the manufacturer. The temperature losses in the PV array have been calculated taking empirical values for fully roof integrated PV modules without ventilation [13]. These losses have been very close (1 % of derivation) to the same scenario simulated with the software PVsyst [14] for the same location for full integrated PV modules, resulting in a theoretical nominal operating cell temperature (NOCT) of 68℃. The ohmic wiring losses result from the used cables at Lake Langano. Taking all losses into account, the performance ratio (PR) of the system is 66 %. Compared to a 70 % PR for PV stand-alone systems in Africa of Szabó et al. [15] we have calculated a slightly more conservative value for the energy system at Lake Langano. The parameters for the LCOE calculation shown in table 2 are based on the experiences made during the assembly of the first prototypes in Ethiopia.

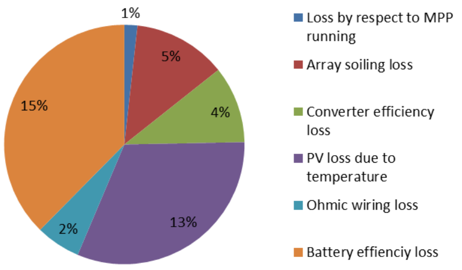

Fig. 10 – *Simulated system losses*

In Figure 11 we show the simulated battery capacity needed and the resulting excess energies to cover the load of approximately 3.5 kWh/d for a whole year without shortages with the same PV system for all scenarios. The load varies for the different scenarios: For the scenario without DSM the daily energy demand is highest with 3.6 kWh/d. This is due to the higher energy demand of the fridge for a scenario without DSM and because the load is not reduced at the rainy seasons as it is done in scenario DSM 2,3 and 4. For scenario DSM 1 and DSM 2 the load is 3.4 kWh/d for DSM 3 it is 3.5 kWh/d due to the energy demand of the water purification system to keep the water always drinkable, even in case of no excess energy. It can be seen that the battery capacity (blue bars) shrinks by the amount of intelligence we bring into the system, whereas the excess energy increases (red bars), thus resulting in an additional service we can offer in scenario DSM 3 by using this energy to purify water. Applying DSM 2 we are able to half the capacity of the battery compared to a system without DSM bringing down the LCOE by 43 % shown in table 3. The LCOE of a diesel generator calculated with crude oil price of 110 USD/bbl is around 0.50 €/kWh [3] making the scenario with DSM 1 an economic and DSM 2 an even more favorable solution. For the DSM 3 scenario 160 m³/a water can be purified for free energy costs resulting in a water price of 3 €/m³, if the water price is to redeem the total cost of the water purification system during the lifetime. As the hydraulic head is assumed by almost the maximum of the capacity of the water pump, the amount of water that is purified can be seen as a worst case scenario. If selling water for this price is a reasonable business case, the DSM 3 scenario would be the one having the greatest potential to lower the energy costs. In table 4 the Performance Ratios (PR) of the energy systems for the different scenarios are compared. For DSM 1 the system efficiency can be improved by 2% by shifting energy consumptions to a time were the produced energy can be used at a maximum efficiency without the need of being stored in a battery. Compared to DSM 2 the PR of DSM 3 is lower because the constant energy demand of the purification system. Evaluating the DSM it can be summed up, that a shift of the load into the daytime (DSM 1) is reasonable. The best results were made if the load can be varied to a certain amount due to the weather conditions (DSM 2) and the resulting excess energy, due to the smaller battery capacity, can be used to run additional variable loads (DSM 3 and DSM 4). By using the fridge as energy sink is it even possible to reduce the LCOE by 57 %.

Table 3 – *LCOE of the different scenarios*

LCOE in €/kWh	no DSM	DSM 1	DSM 2	DSM 3	DSM 4
PV stand-alone system	0.60	0.47	0.34	0.27	0.26
PV stand-alone system, incl. kiosk	1.02	0.91	0.79	0.72/1.43[1]	0.71

[1] LCOE, incl. costs for the water purification system

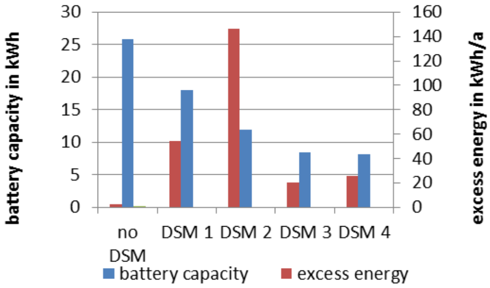

Fig. 11 – *Comparison of the battery capacity and excess energy according to the load curve*

Table 4 – *Performance ratios of the different scenarios*

	no DSM	DSM 1	DSM 2	DSM 3	DSM 4
PR	66%	68%	73%	70%	73%

Figure 12 shows the cost advantage of PV-battery systems as it is used in the SOLARKIOSK vs. diesel systems in a broader perspective. The load curve is based on the scenario DSM 1, but for each location shown below the battery and PV generator is sized individually in given steps according to the modularity of the SOLARKIOSK to match the best LCOE. 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 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.

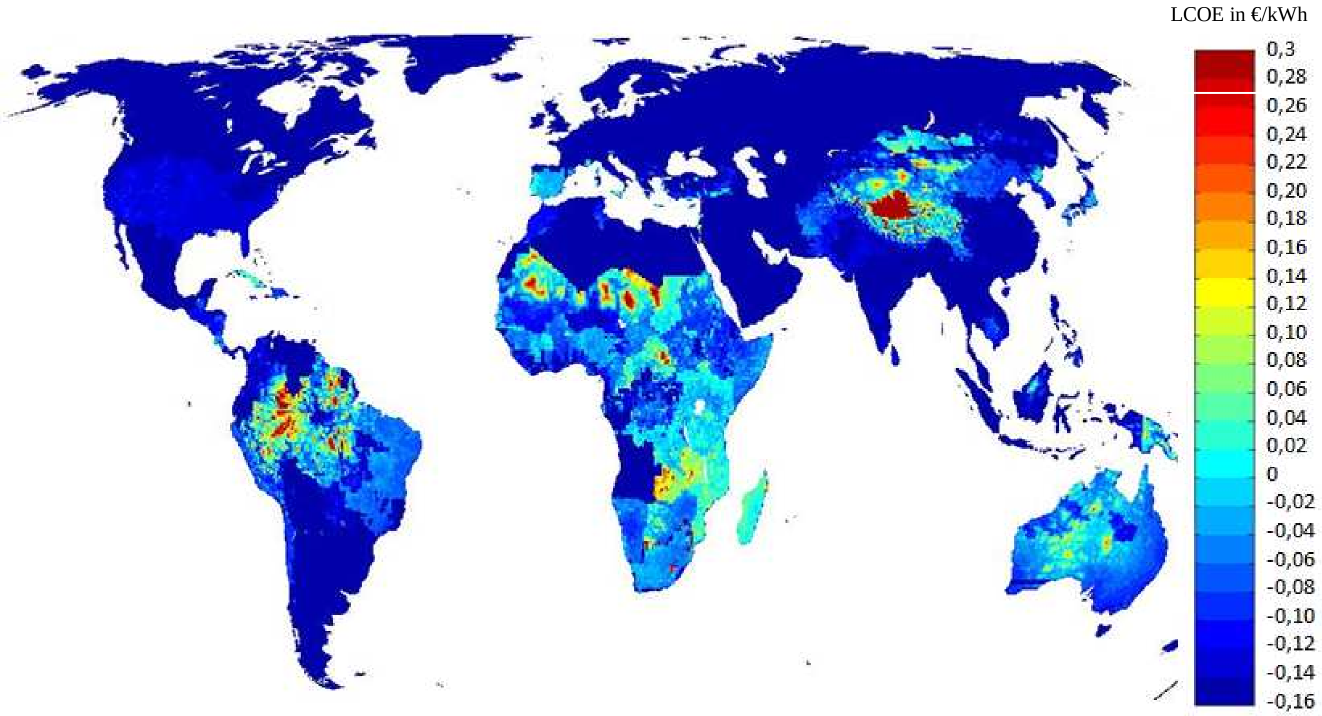

Fig. 12 – *Cost advantage of PV-battery systems vs. diesel generator systems*

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 12. The highest cost reduction can be done by adding a more sophisticated DSM, as we have shown for the SOLARKIOSK at Lake Langano by using the fridge as an energy sink. This has led to a cost reduction of 45% (DSM4 vs. DSM 1) and should therefore be implemented in the SOLARKISOK to make it even more competitive to a diesel alternative.

IV. CONCLUSION/ OUTLOOK

It is shown, that a careful system design for a PV-based kiosk combined with a demand side management resulting in reduction of the battery capacity is an economic solution to provide energy in remote off-grid areas in Ethiopia and in other Sub-Saharan countries. Controlling the load has the potential to bring down energy costs radically and should be applied to a stand-alone PV system as it offers the opportunity to replace diesel generators. This should be taken as motivation to continue developing the DSM by adding intelligence to the fridge such as cooling it down in time of high irradiation and switching it off, in order to decrease the battery capacity.

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