Chapter 6

Promoting Rural Electrification in Sub-Saharan Africa: Least-Cost Modelling of Decentralized Energy-Water-Food Systems: Case Study of St. Rupert Mayer, Zimbabwe

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Abstract The outstanding solar potential in Sub-Saharan Africa (SSA) enables significantly cheaper levelized costs of electricity for decentral solar systems compared to the commonly used diesel generators. Yet, the limited purchase power in SSA impedes rural electrification by solar systems due to their high investment costs. Decentralized Energy-Water-Food systems (EWFS) have the potential to solve this problem. Using solar-powered water pumps, rural communities can supply water for drinking and irrigation. Thereby, agriculture does not depend on rainfall solely and can be done all over the year, which leads to increasing productivity. The increased crop production reduces the community's expenses for nutrition and enables profit by sales, which in turn enables a payback of the initial investment costs of the solar system. The increased amount of biomass waste enables economically feasible small-scale biogas production. The biogas can be used for electricity production by biogas motors. These can supply private, social or small commercial loads, which enhance the local productivity even more. To identify the least-cost system design regarding the supply of electricity, water and food for the rural village of St. Rupert Mayer, Zimbabwe, the linear optimization model *urbs* was adapted. *urbs* was developed for energy system modelling, yet its sector coupling feature allows to add processes like water pumps and commodities such as biogas. The modelling results show that a holistic system including photovoltaics (PV), water pumps, enhanced agriculture and biogas production reduces the levelized costs of electricity (LCOE) from 0.45 USD/kWh by power supply from diesel generators to 0.16 USD/kWh. The modelling results shall support local governments and entrepreneurs in their decision-making.

Keywords Decentralized renewable energy solutions • Energy-Water-Food systems • Biogas • Least-cost modelling • Economic development

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6.1 Introduction

“Access to affordable, reliable, sustainable and modern energy for all” is one of the 17 sustainable development goals (SDG) set by the United Nations [1]. Economic growth is hindered by insufficient, unreliable and expensive availability of electricity and is felt by consumers of all sizes [2]. However, at this moment a total of 1.3 billion people worldwide have no access to electricity, 600 million of whom live in Sub-Saharan Africa (SSA) [3]. While the extraordinary potential for solar energy in SSA allows for a low levelized cost of electricity (LCOE) by means of photovoltaics (PV), which is lower than electricity generated by conventional fossil fuels, the share of solar and wind energy in primary energy consumption in SSA is currently smaller than 0.1% [3]. A major reason for this is the high interest rates typically found in SSA in combination with low purchasing power of the masses. These have an especially negative impact on investments in volatile renewable energy (RE) technologies since these have typically higher specific investment costs than conventional fossil fuel powered energy production units. This negative effect of limited purchasing power on the implementation of RE systems is further aggravated by the additional need for investment in storage and control systems. Thus, in off-grid regions the loads have to be optimized to minimize storage costs while increasing the local productivity to justify the investment in PV. Solar water pumps are a good example of such loads as they can be used flexibly and add to agricultural productivity by the pumped water. Another advantage of these decentralized Energy-Water-Food systems (EWFS) is that the resulting biomass residue can produce cost-effective biogas. This can be used to compensate the volatile PV electricity production using cheap generators.

6.2 Literature Review

The conceptualization of decentralized EWFS was driven by large-scale studies on software-based optimal planning and sizing of hybrid renewable energy systems (HRES), which propose the integration of renewable, traditional energy technologies and energy storages [4]. The complexity of these integrated energy supply systems is approached through cost-optimal modelling, simulation and optimization tools such as SOLSTOR, SOLEM and HOMER, reviewed in [5]. These tools dimension energy systems based on economic criteria as the total net present cost (TNPC) or levelized cost of energy (LCOE). The aim is to propose cost-feasible system configurations in contrast to other software tools, which optimize technical parameters such as the overall system efficiency [6]. Cost-optimal HRES are the most widely spread state-of-the-art solution for sustainable rural development through reliable and cost-effective electricity supply [5]. The economic feasibility of the proposed system designs has been positively measured through the impact on the agricultural sector. Agriculture is one main primary source of income and of

local food supply [7]. By performing pre-analysis and calculations related to agricultural processes outside the optimization tools, the model outputs fit closely to the rural reality. Hence, several studies assess load requirements for agricultural irrigation apart from the domestic load [8, 9]. Another approach is the scheduling of daily irrigation according to the operation of photovoltaic-powered water pumping systems [10, 11]. Research is also effectuated on the usage of crop residues to power cost-free fuelled biomass generators [12] or the generation of biogas through anaerobic fermentation as well as from crop residues use in order to power biogas generators [13, 14]. These pre-analysis calculations carried out before the simulation address the dependency of agricultural processes (water and food systems) on energy technologies, portrait the local eco-system more competently and assess rural development goals.

However, a key desirable feature is the direct modelling and simulation of processes relevant to EWFS in cost-optimizing HRES software in order to properly dimension the integrative decentralized system. Studies approaching the EWF nexus highlight the need for integrative solutions that consider the synergies among the components of EWFS and assess the connections between the three subsystems [15, 16]. Existing tools address the interdependencies of these complex systems from project management-based frameworks [17] or techno-ecological methodologies like resource management [16]. Hence, this research aims to contribute to the current research status-quo by assessing the economic feasibility of EWFS with least-cost modelling. This is achieved with *urbs*, a linear optimization model developed at the Chair of Renewable and Sustainable Energy Systems, Technical University Munich (TUM), Germany. All previous studies on *urbs* have focused on grid-connected [18, 19] or off-grid [20] energy systems. *urbs* allows, however, the modelling of cross-sector systems as transformation processes of input and output resources and the optimization of the integrated system. The results show the optimal planning and operation for the holistic EWFS. Furthermore, the trade-offs across the energy-water-food nexus and the associated impact can be analysed. The workflow is outlined in the next section.

6.3 Methodology

This study uses the model *urbs* for the analysis of the EWF system scenarios in decentralized off-grid rural areas. *urbs* is an open-source linear optimization tool programmed in the language Python. It is an economic model and identifies the optimal system configuration that meets a predetermined resource demand with respect to the economic feasibility. This is given by the minimal variable total costs resulting from the techno-economic modelling of each process, transmission and storage technologies in the system. Furthermore, *urbs* offers features for the design of buying and selling processes, intertemporal optimization as well as demand-side

Fig. 6.1 One-node modelling of EWFS with *urbs*

management, and allows configurable time and space resolution (one-node or multiple-node system) [18]. The complete mathematical description of *urbs* can be found in [21].

Figure 6.1 shows the schematic EWFS framework with the main input and outputs. This work focuses on the off-grid one-node system, characterized by local weather conditions, demand, resource availability and site topography. There are market-based prices for purchasing and selling of selected resources and all EWF processes and storages are subject to local techno-economic parameters. The model outputs listed in Fig. 6.1 are obtained under the main restriction of satisfying the hourly EWF demands. The proposed model is tested on a Zimbabwean use case village.

St. Rupert Mayer (SRM), a village in rural Zimbabwe with 250 inhabitants, was chosen as a case study for the modelling of an EWFS was chosen. The long-term cooperation between SRM and TUM facilitated the acquisition of required input data for the model regarding demand and supply of power, water, agriculture and food. Based on the nominal power of residential applications and their temporal utilization patterns, a Monte Carlo Simulation was conducted to create an hourly electrical load profile for SRM [22]. The daily water demand is 50 l per person, the daily food demand is represented by 600 g wheat per person, which covers the required 2200 kcal per day [1]. The demand time series for power, water and food include just residential consumption, additional loads such as the power demand by water pumps are implemented as possible processes. Because of the unreliability of the grid connection, SRM is assumed to be off-grid regarding the modelling. Power supply is possible by diesel generators, biogas generators, PV and batteries. The time series for global horizontal radiation in SRM has been created with “PVWatts” and converted into hourly capacity factors for PV [22]. Water can be purchased by water trucks for 0.80 USD/m³ or supplied by water pumps and stored in water tanks. Wheat can be purchased and sold on the local market for each 0.45 USD/kg or supplied by local farming. Because of the missing water grid connection and the unreliable power grid, presently farming in SRM is just possible in small scales

Fig. 6.2 Scheme of EWFS

during rainy season. In the model, just farming by means of groundwater pumping is taken into account. The wheat straw can be used as free fuel for a biogas digester in order to generate fuel for the biogas generator. Based on questionnaires, the variable costs of the process *Field* represent an annual income of 750 USD for farmers in SRM. The maximum capacity for farming is set to 10 ha and for groundwater to 300,000 m³ per year, both based on values during peak productivity in the 1990s. Although SRM is modelled as a “green field” in order to give generic results, all described Energy-Water-Food processes are or have been implemented in SRM. Thus, it was possible to acquire the locally occurring CAPEX and OPEX for these processes by questionnaires in SRM [23]. General techno-economic process parameters are defined based on literature research, e.g. the weighted average cost of capital (WACC) is set to 15%. All model assumptions are listed in the appendix.

The investigated scenarios are distinguished by the amount of implemented demand-commodities, processes and storages. Scenario 1 represents a simple diesel island system, scenario 9 includes all possible processes of the modelled EWFS as shown in Fig. 6.2 (Table 6.1).

6.4 Results and Discussion

Figure 6.3 shows a result plot for the least-cost power generation with *urbs*. The black line is showing the implemented power demand, the additional demand due to the water pump is visualised as a negative power producer. The power producers *Diesel Generator* and *Photovoltaics* generate sufficient electricity to cover both types of demand including storage losses. The excessive power being produced by PV is causing dump load, “*Shunt(Elec.)*”, which is shown as a negative producer as well.

Table 6.1 Modelled scenarios

#	Title	Modelled demands, processes, and storages etc.
S1	Diesel	Electricity (E) <i>demand</i> + Diesel (D) <i>buy</i> + Diesel Generator (DG)
S2	+PV	S1 + Photovoltaic (PV) + Electricity (E) <i>dump load</i>
S3	+Battery	S2 + Battery (Bat)
S4	+Water Demand	S3 + Water (W) <i>demand</i> + <i>buy</i>
S5	+Water Pump	S4 + Water Pump (WP) + Water Tank (WT)
S6	+Food Demand	S5 + Food (Fo) <i>demand</i> + <i>buy</i>
S7	+Fields	S6 + Field (Fie)
S8	+Food Selling	S7 + Food (Fo) <i>sell</i>
S9	+Biogas	S8 + Biogas Digester (BD) + Biogas Tank (BT) + Biogas Generator (BG)

Fig. 6.3 Power generation time series for one week in kW—Scenario “+Fields”

Figure 6.4 shows the least-cost power generation mix for each scenario. As soon as PV is allowed to be installed from scenario “+PV” on, it generates a relevant share of power, yet the Diesel generator continues to supply power during night hours. For all scenarios including power generation with PV, the least-cost generation includes overproduction by PV and thus dump load, even if batteries are allowed, which can be observed in Fig. 6.3. The use of water pumps leads to increasing PV capacity and decreasing battery capacity or dump load because the water pump is working as a flexible load. This effect is minor for the supply of private water demand in scenario “+Water pump”, yet increases significantly in case of increased water supply for agriculture in the scenarios “+Fields” and “+Food selling”. In this scenario, the maximum available land of 10 ha is completely used. In scenario “+Biogas” there is no more power generation from PV and just a slight generation from diesel generators. The selling-oriented agriculture results in 342 t of straw, which can be used as free fuel for the biogas digester and its energy content of 530 MWh exceeds the total power demand of the EWFS by far.

As shown in Fig. 6.5, the LCOE decrease from 0.45 to 0.38 USD/kWh if power can be generated by diesel generators and PV. The introduction of batteries and

Fig. 6.4 Annual power generation in kWh for each scenario

Fig. 6.5 LCOE and annual costs per capita for each scenario

water pumps for private water demand reduces the LCOE just minimally. Yet, the increased water pump capacities of the scenarios “+Fields” and “+Food Selling” reduce the LCOE significantly to 0.34 and 0.31 USD/kWh, respectively. This is due their cost-efficient utilization during the day, as shown in Fig. 6.3. The introduction of biogas leads to a further reduction of the LCOE to 0.16 USD/kWh, because of the moderate CAPEX of both processes, low storage costs for the biogas tank and the sufficient availability of straw as free input of the digester. The described reductions of LCOE lead to reductions of annual costs per capita, as it can be seen in Fig. 6.5. However, the annual costs rise in the scenario “+Water demand” and especially in the scenario “+Food demand” because of the additional costs for water and food, which have to be purchased as shown in Fig. 6.6. The scenarios “+Water Pump” and “+Fields” show significantly lower annual costs than these because water and food are now self-supplied by water pumps and fields on lower costs. The revenue by selling wheat in the last two scenarios leads to a drastic cost reduction.

Fig. 6.6 Annual system costs in USD per year for each scenario

29 USD per year and person in scenario “+Biogas” is remarkable, because these expenses cover the consumption of power, water and food per capita. The identical demand causes annual costs of 227 USD per person in scenario “+Food demand”. The expenses on fuel and purchase of food dominate this scenario’s costs, but there is no revenue from sales. The system costs in the last scenario are actually higher than the ones of scenario “+Food demand”, yet almost offset by the revenue of the wheat sales. Furthermore, its system costs are not caused by fuel and purchase but are dominated by variable costs. These are caused by the high maintenance costs of the biogas digestion and in particular the salary for farmers, which also occur in scenario “+Fields” and “+Food selling”. Based on the resulting variable costs, this scenario leads to the creation of 60 jobs in agriculture. The job creation could be even higher if more cultivatable land would be available. Figure 6.6 shows also, that in no scenario the CAPEX (“invest”) are dominating, mostly due to the purchasing costs for diesel. In the last scenario, no investment-intensive PV is installed anymore.

6.5 Conclusion and Recommendations

The results show the techno-economic benefits of decentralized EWFS. The use of solar-powered water pumps enables sufficient water supply at low costs for enhanced agriculture. The increased agricultural productivity leads to revenues by crop sales, job creation in farming, and big quantities of crop waste like straw, which can be converted on low costs to biogas and thus power the whole system. Both the biogas generation and utilization as well as the revenues by crop sales reduce the total system costs for the supply of power, water and food to less than 11% of the costs occurring in case of power generation with diesel and water and

food purchase from the market. Additionally, the job creation in agriculture creates local purchase power, which enables to pay off the investment costs of the system.

Further model improvement will address: Implementation of rainfall time series, modelling groundwater as storage, enhanced soil analysis, fertilizer demand, fertilizer supply by commercial ones or residues from biogas digester, life-cycle-analysis for soil nutrients, additional field crops, variation of crop prices, livestock farming, food processing, other electrical loads from commercial and social sector, heat demand for cooking, heat supply by firewood and biogas, labour as commodity.

Additionally, the obtained results have to be implemented to identify obstacles, which are not covered by the model yet, such as required technical expertise. Based on these findings, governments, entrepreneurs and other local stakeholders shall be able to promote electrification and economic development of rural regions in SSA by means of EWFS.

Appendix 1: Techno-Economic Input Parameter

See Tables 6.2, 6.3, 6.4, 6.5, 6.6, 6.7, 6.8, 6.9, and 6.10.

Table 6.2 Techno-economic parameters for diesel generator [20, 24, 25]

	Unit	Value
Investment costs	US\$/KW	240
Fixed O&M costs	US\$/KW/year	5% of investment costs
Variable O&M costs	US\$/kWh	0.024
Diesel price	US\$/kWh	0.1
Load efficiency	%	25
Depreciation time	year	20

Table 6.3 Techno-economic parameters for solar photovoltaics [20, 26]

	Unit	Value
Investment costs	US\$/kW	1600
Fixed O&M costs	US\$/kW/year	2% of investment costs
Modular efficiency	%	16.7
Depreciation time	year	20

Table 6.4 Techno-economic parameters for water pumps [27, 28]

	Unit	Value
Investment costs	US\$/kW	900
Fixed O&M costs	US\$/kW/year	5% of investment cost
Total dynamic head	m	70
Pump efficiency	%	80
Depreciation time	year	15

Table 6.5 Techno-economic parameters for wheat fields [29–31, 39, 40]

	Unit	Value
Max capacity of fields	ha	10
Variable O&M costs	US\$/ton	247.73
Average wheat yield	ton/ha	6
Wheat growth time	day	120
Max cycles per year	–	3
Labor requirements	farmer/ha	6
Wheat ratio to wheat plant	%	35
Wheat waste ratio to wheat plant	%	65
Wheat plant water requirements	m ³ /ton	263.58
Depreciation time	year	20

Table 6.6 Techno-economic parameters for biogas digester [32–34, 36, 41, 42]

	Unit	Value
Investment costs	US\$/kW	500
Fixed O&M costs	US\$/kW/year	2% of investment costs
Variable O&M costs	US\$/kWh	0.024
Calorific energy in 1 m ³ biogas	kWh	6.2
Biogas yield from wheat	m ³ /ton	450
Biogas yield from wheat waste	m ³ /ton	250
Depreciation time	year	20

Table 6.7 Techno-economic parameters for lithium battery [20, 35]

	Unit	Value
Investment cost (Energy)	US\$/kW	250
Investment cost (Power)	US\$/kWh _{el}	350
Fixed cost (Power)	US\$/kW/year	2% of investment costs (Power)
Fixed cost (Energy)	US\$/kWh _{el} /year	10
Variable cost (Power)	US\$/kWh _{el}	0.02
Input efficiency	%	95
Output efficiency	%	95
Initial state of charge (SOC)	%	50
Depreciation time	year	10

Table 6.8 Techno-economic parameters for biogas generator [36–38, 43]

	Unit	Value
Investment costs	US\$/kW	400
Fixed O&M costs	US\$/kW/year	5% of investment costs
Variable O&M costs	US\$/kWh _{el}	0.02
Efficiency	%	30
Depreciation time	year	20

Table 6.9 Techno-economic parameters for water tank

	Unit	Value
Investment costs	US\$/m ³	30
Depreciation time	year	20

Table 6.10 Techno-economic parameters for biogas storage

	Unit	Value
Investment costs	US\$/kWh	16.13
Depreciation time	year	20

Appendix 2: Time Series for Least-Cost Power Generation and Storage

See Figs. 6.7, 6.8, 6.9, 6.10, 6.11, 6.12, 6.13, 6.14, and 6.15.

Fig. 6.7 Time series for least-cost power generation for one week in kW—Scenario “Diesel”

Fig. 6.8 Time series for least-cost power generation for one week in kW—Scenario “+ PV”

Fig. 6.9 Time series for least-cost power generation and storage for one week in kW—Scenario “+ Battery”

Fig. 6.10 Time series for least-cost power generation and storage for one week in kW—Scenario “+ Water Demand”

Fig. 6.11 Time series for least-cost power generation and storage for one week in kW—Scenario “+ Water Pump”

Fig. 6.12 Time series for least-cost power generation and storage for one week in kW—Scenario “+ Food Demand”

Fig. 6.13 Time series for least-cost power generation and storage for one week in kW—Scenario “+ Fields”

Fig. 6.14 Time series for least-cost power generation and storage for one week in kW—Scenario “+ Food selling”

Fig. 6.15 Time series for least-cost power generation and storage for one week in kW—Scenario “+ Biogas”

Appendix 3: Output Parameter

See Tables 6.11, 6.12, 6.13, 6.14, 6.15, 6.16, and 6.17.

Table 6.11 Installed process capacities for each scenario

#	DG [kW]	PV [kW]	BG [kW]	BD [kW]	WP [kW]	Fie [ha]
S1	35.87	0	0	0	0	0
S2	35.87	23.16	0	0	0	0
S3	29.55	25.43	0	0	0	0
S4	29.55	25.43	0	0	0	0
S5	29.84	25.79	0	0	0.40	0
S6	29.84	25.79	0	0	0.40	0
S7	31.55	31.02	0	0	5.52	2.89
S8	35.32	46.03	0	0	15.68	10
S9	8.7	0	27.17	47.38	4.78	10

Table 6.12 Installed storage capacities for each scenario

#	Bat [kWh]	WT [m ³]	BT [kWh]
S1	0	0	0
S2	0	0	0
S3	14.57	0	0
S4	14.57	0	0
S5	13.68	10.48	0
S6	13.68	10.48	0
S7	9.25	9.36	0
S8	0.58	7.28	0
S9	0	0.52	222.29

Table 6.13 Energy, water and food quantities for each scenario

#	Energy [kWh]	Water [m ³]	Wheat [ton]	Straw [ton]
S1	86,104.07	0.00	0.00	0
S2	86,104.07	0.00	0.00	0
S3	86,104.07	0.00	0.00	0
S4	86,104.07	4555.20	0.00	0
S5	87,188.65	4555.20	0.00	0
S6	87,188.65	4555.20	52.56	0
S7	96,613.15	44,138.14	52.56	97.76
S8	12,0174.43	143,095.48	183.96	342.17
S9	120,174.43	143,095.48	183.96	342.17

Table 6.14 Bought and sold commodities for each scenario

#	Diesel buy [kWh]	Water buy [m ³]	Wheat buy [ton]	Wheat sell [ton]
S1	344,416.30	0	0	0
S2	232,345.65	0	0	0
S3	209,640.59	0	0	0
S4	209,640.59	4555.20	0	0
S5	211,093.85	0	0	0
S6	211,093.85	0	52.56	0
S7	204,405.85	0	0	0
S8	203,194.48	0	0	131.40
S9	2239.50	0	0	131.40

Table 6.15 Power generation mix for each scenario

#	DG [kWh]	PV [kWh]	BG [kWh]
S1	86,104.07	0.00	0
S2	58,086.41	37,130.61	0
S3	52,410.15	40,764.24	0
S4	52,410.15	40,764.24	0
S5	52,773.46	41,345.52	0
S6	52,773.46	41,345.52	0
S7	51,101.46	49,736.43	0
S8	50,798.62	73,794.97	0
S9	559.88	0.00	119,614.55

Table 6.16 System costs in USD per year for each scenario

#	Revenue	Invest	Fuel	Fixed	Variable	Purchase
S1	0	1375.39	34,441.63	430.45	2066.50	0
S2	0	7295.19	23,234.56	1171.53	1394.074	0
S3	0	8963.29	20,964.06	1345.55	1437.085	0
S4	0	8963.29	20,964.06	1345.55	1437.085	3644.16
S5	0	9102.14	21,109.39	1368.23	1431.906	0
S6	0	9102.14	21,109.39	1368.23	1431.906	23,652.00
S7	0	10,894.64	20,440.59	1733.96	14,374.95	0
S8	-59,130.00	15,635.90	20,319.45	2610.87	46,800.69	0
S9	-59,130.00	7164.73	223.95	1336.48	57,547.30	0

Table 6.17 LCOE and annual costs per capita for each scenario

#	LCOE [c/kWh]	Annual costs per capita [US\$/year]
S1	44.50	153.30
S2	38.40	132.40
S3	37.90	130.80
S4	37.90	145.40
S5	37.70	132.00
S6	37.70	226.65
S7	34.40	189.78
S8	30.50	104.95
S9	16.40	28.57

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