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When More Than Money Talks: Multi-Criteria Decision Analysis of Fuel Cells for Sustainable Power Supply in Sub-Saharan Minigrids

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ABSTRACT

Strategies of countries in Sub-Saharan Africa include minigrid deployment in order to progress towards providing access to electricity to the currently 500 million people living without access in rural areas by today. While recent studies on fuel cells in such minigrid energy systems are limited to technical and economic considerations, this paper performs a multi-criteria decision analysis to compare their fit into the economic, technical, environmental, and social system against established fossil and renewable power generation technologies.

Findings from scenarios which shed light on 1. strategically important criteria according to academic expert opinions captured in a survey, 2. decisive criteria for actual market penetration of power generation technologies in the respective setting and 3. future parameter and criteria in alliance with sustainable development, indicate the fuel cell to be highly suitable for rural power generation in minigrids. The major disadvantage of low economic performance of decentralized hydrogen production and usage by fuel cells in minigrids could be overcome by large-scale centralized water electrolysis. But as reliability of supply and synergies to other end-uses are promising, the authors suggest to direct future work to define economic niches and use-cases for decentralized hydrogen production in minigrids.

Index terms: *Access-to-energy, sustainable electrification, fuel cell, hydrogen, multi-criteria decision analysis, rural minigrid, technology evaluation criteria, expert survey.*

I. INTRODUCTION

As electricity is proven to be a fundamental pillar of human development as a collective term for economic [1], cultural and social development [2], efforts in sustainable electrification have gained increasing momentum in the past decade [3]. However, nine years before completion of the Sustainable Development Goal (SDG) period, the target of universal electrification is in great distance with still 600 million people having no access to electricity in Sub-Saharan Africa (SSA) only [3]. Especially and unproportionally affected is the rural population where only three out of ten people had reliable access to electricity in 2018 [4]. Strategies and blueprints of countries facing forced action to progress towards rural electrification rely on combined approaches of grid extension, deployment of Solar Home Systems and isolated minigrids. Filling the niche in between the two aforementioned extrema, minigrids combine acceptable deployment complexity and comparatively low costs with a high Tier-level of supply [5]. With this, minigrids are considered to be the most suitable electrification pathway for more than a half of the population currently living without access to electricity (52.5%) [6].

As the common range of demand in such minigrids allows for a variety of power generation technologies to be integrated, fuel cells, converting hydrogen into electricity, have increasingly gained attention in the recent past [7]. Besides its use for power production, hydrogen can in addition be utilized as clean cooking fuel [8], as a motive fuel for mobility [9] or as a base substance in agricultural fertilizer [10], making hydrogen an all-round talent in the field of isolated minigrids.

However, whilst research on the application of hydrogen technologies in isolated Global North settings are abundant – with common objects of investigation being single houses [11-17], small island or remote villages [18, 19], industrial applications [20] or stand-alone systems which require uninterruptible power supply [21-24] – considerations for Global South minigrids still remain limited, both in number and scope. Most studies apply modeling tools to assess the techno-economic potential of fuel cells in minigrid energy systems [25-29]. A very comprehensive technical review on their integration in microgrids is provided by Akinyele et al. [7]. Documentation of demonstration projects, such as the "Sunfold" (Tiger Power) product deployment, combining a reversible

fuel cell system, solar photovoltaic (PV) and battery storage in a container solution in Uganda minigrids [30], is limited to technical description, or economic considerations in other cases [31]. Just recently (March 2021), SFC Energy has announced to deploy 48 fuel cells of 500W each in rural northern India to electrify isolated communities [32].

With increasing knowledge about interlinkages between SDG 7 and other dimensions of development [33] the belief grows that power generation technologies must not only be evaluated by their technical capabilities or economic performance but rather their holistic fit into the economic, technical, environmental and social system [34]. History of technology development has shown technical frontrunners to fail in long-lasting energy supply, as the technologies have not been accepted by the users, ending up abandoned. Likewise, energy technologies harming the environment are continuously losing market share, as recent policies and regulations penalize such operations in the long-term.
In order to capture the holistic potential of fuel cells for sustainable power supply in rural minigrids and evaluate their competitiveness against established fossil and renewable technologies, this paper performs a multi-criteria decision analysis (MCDA) on seven power generation technologies, and opens the discussion to include technical, environmental, economic and social criteria to compare the technologies. Introducing scenarios to include expert opinions, characteristics currently decisive for market success and potential future developments, the analysis additionally sheds light on strategically important and future perspective technology parameter.

Following the sequence of a MCDA method, illustrated in Figure 1, the material and methods section first defines system boundaries and technologies. Subsequently, subsection Criteria selection presents the methods used to define a compact set of relevant evaluation criteria, combining thorough literature review with statistical analysis. The Scenario development section develops three scenarios to introduce subjective weights to the defined evaluation criteria, including weights according to an academic expert survey, criteria decisive for current market shares of established power generation technologies and future development of technologies and political ambition. The Results briefly present strengths and weaknesses of the fuel cell technology before highlighting a ranking of the compared technologies. Main findings are taken up by the Discussion, which is additionally fed with statements of an expert survey. The researchers conclude with a summary of findings and suggestions for future work.

II. MATERIAL AND METHODS

A. Technology Selection and System Boundaries

The following section introduces the scope of technologies considered in the MCDA and their main characteristics. Special attention is paid to the fuel cell and considered system boundaries.

- As the definition of a minigrid is broad in scope, with only the characteristic of being founded on a decentralized form of energy generation that relies on local infrastructures for generation and distribution [38-40] to be consistent in available descriptions, criteria must be defined to limit the scope of technologies included in the analysis. In the present paper, the following restrictions have been made.

- As 'generation' is by far the core functionality of minigrids [39] being most prominent discussion to minigrid developer and users, the analysis only considers power generation technologies. This excludes any 'conversion', 'consumption', 'control, manage and measure' and 'storage' devices.

- As the paper considers technologies rather than energy systems, hybrid systems or any (partly) interaction with a connected grid are excluded.

- To fit in the common approach of defining minigrids by the total installed generation capacity, with common thresholds being 100 kW [40], 1 MW [41], or even 10 kW – 10 MW [38, 42], technologies considered in the analysis must be scalable in a range between 10 kW and 1 MW.

- Technologies considered must not be restricted to extremely specific environmental conditions, but must be applicable across a broad spectrum on the SSA mainland, excluding e.g. tidal current power generation.

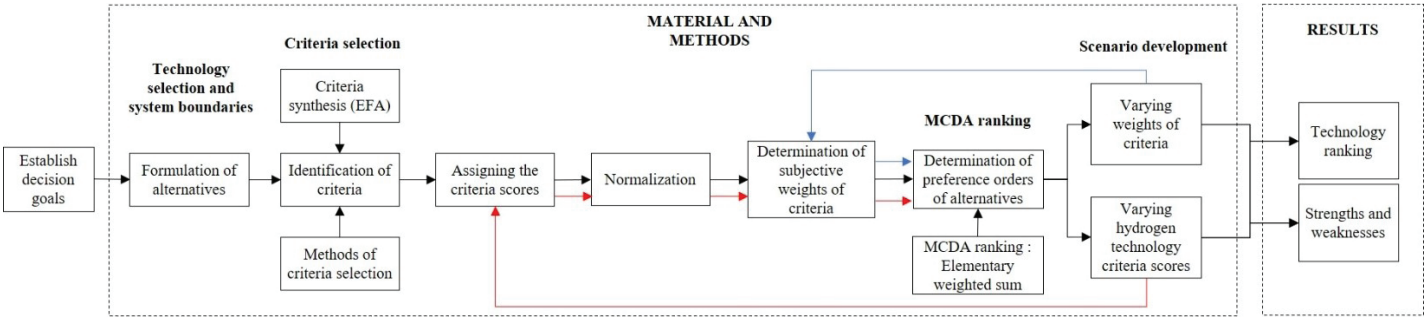

Fig. 1. Simplified and adjusted MCDA process in sustainable decision making [35-37].

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- Technologies considered must not only be proposed in literature or research, but evidence on recent operation in a SSA minigrid must be present, excluding e.g. geothermal and concentrated solar power generation.

Applying these criteria reduced an initial set of power generation technologies proposed for autonomous minigrids by the World Bank [43] to seven unit types, including the biogas power system, diesel generator, micro-hydropower, micro-gasturbine, micro-windturbine, solar photovoltaic (PV) and the fuel cell. An issue of discussion regarding fuel cell systems is whether to utilize on-site or off-site generated hydrogen. Therefore, the paper distinguishes between both possibilities. While the usage of off-site produced hydrogen meets the above listed criteria, the conversion of on-site produced hydrogen requires to consider additional technologies for primary electricity generation and its conversion into hydrogen at first, which this paper on exemption allows to be included in the analysis.

Figure 2 therefore differentiates between the distinct options of hydrogen integration with ascending level of self-sufficiency, being a) off-site production of hydrogen, and b) on-site production of hydrogen and utilization by a (regenerative) fuel cell. As indicated by the dashed lines, the system boundaries for the on-site case b) includes any primary electricity generation technology, notably effecting the results in later stage. As such upstream technology the best performing renewable technology is considered in each respective evaluation criteria later.
Although Figure 2 proposes a separated electrolyzer and fuel cell for the on-site production and utilization of hydrogen, the two systems may be integrated and operated in dual mode, called a regenerative fuel cell, that is they may be operated as an electrolyzer and alternately as fuel cell [7]. For a more detailed technical description of the integration of hydrogen in isolated minigrids the researchers refer to Akinyele et al. [7], while Buttler and Spliethoff provide a recent and comprehensive study on technical and economic key characteristics of hydrogen systems [44].

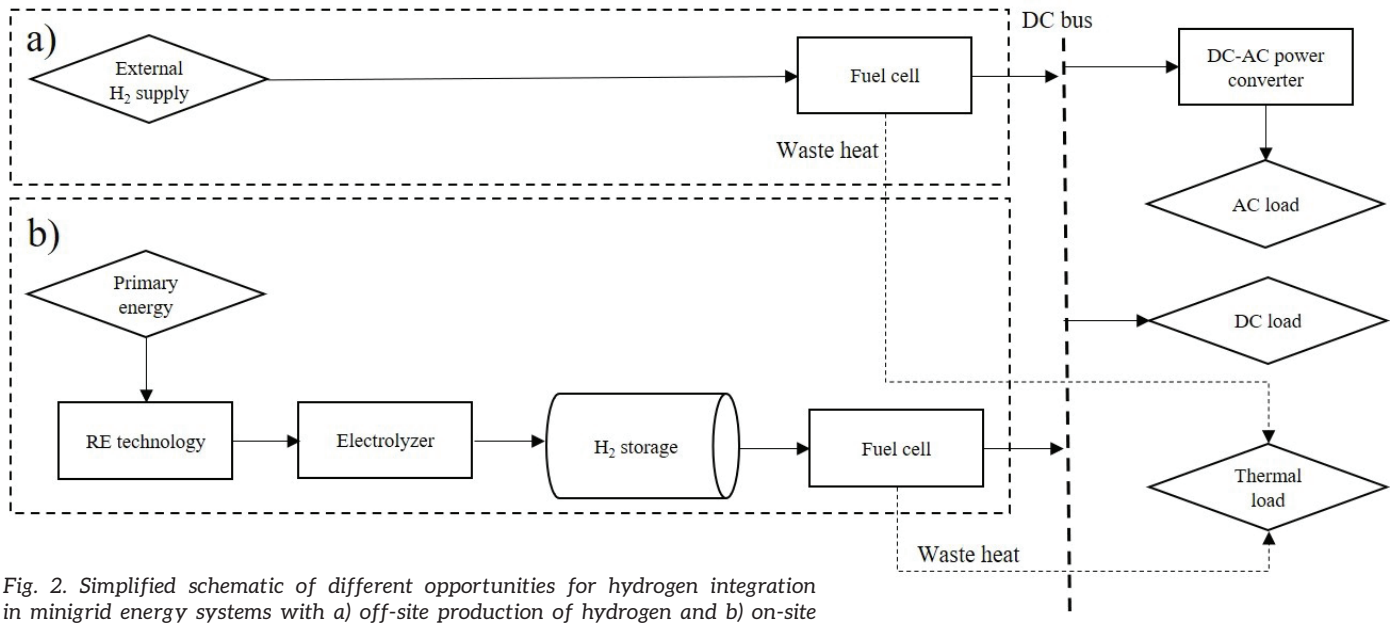

Fig. 2. Simplified schematic of different opportunities for hydrogen integration in minigrid energy systems with a) off-site production of hydrogen and b) on-site production and utilization of hydrogen.

As the technologies considered in the MCDA might vary in their individual technical construction and therefore characteristics, the analysis generalizes such differences in construction to include evidence from different literatures according to the description of technologies contained within Table 1.

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TABLE I
MAIN CHARACTERISTICS OF ASSESSED POWER GENERATION TECHNOLOGIES [38, 39, 41, 43, 45-47].

Technology label	Technology characteristics	Current use
Biogas Power System	• Solid biomass feedstock (considered renewable) converted by means of an anaerobic gasifier to produce biogas for combustion with power production unit. • Biomass slurry remains as side-product. • Typical unit capacity: 10 kW – 1 MW	Biogas is predominantly used as cooking fuel but also for electrification purposes.
Diesel generator	• Stationary diesel fueled internal combustion engine, excluding diesel storage. • Typical unit capacity: 1 kW – 1 MW	Currently the most used technology for rural electrification in SSA.
Pico-/Micro-hydropower	• Run-of-river or tributary pico- and micro hydropower units. • Typical unit capacity:1 kW – 1 MW	Mature technology often used in South-East Asia, emerging in SSA.
Micro-gas turbine	• Small scale turbine engine that runs on natural gas. • Typical unit capacity: 30 kW – 200 kW	Widely used technology for rural electrification in SSA.
Micro-wind turbine	• Onshore horizontal axis turbines with varied generator type. • Typical unit capacity: 1 kW – 1 MW	Widely used technology for rural electrification in SSA.
PV	• Residential, commercial or industrial installations of photovoltaic solar panels, including power controlling devices. Generally, our data sources do not specifically distinguish among the different panel manufacturing technologies. • Ground mounted system considered. • Typical unit capacity: 1 kW – 1 MW	Widely used for stand-alone systems (Solar Home Systems) as well as in minigrids.
a) Fuel cell	• PEM or AEL/AFC and fuel cell of no specific type that runs on off-site produced hydrogen, assumed to be generated by natural gas reforming. • Typical unit capacity: 10 kW – 1 MW	Pilot tests for electrification.
b) Regenerative Fuel cell	• PEM or AEL/AFC electrolyzer and fuel cell of no specific type that runs on on-site produced hydrogen, including any upstream renewable power generation technology to be assumed the best performing technology of each evaluation criteria. • Typical unit capacity: 10 kW – 1 MW	Pilot tests for electrification and as clean cooking fuel.

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B. Criteria Selection

As the definition of criteria for decision making in technology evaluation is highly complex and requires both theoretical background as well as practical expertise, a mixed method approach was applied, combining thorough literature study and statistical analysis.
The literature research focused on previous studies which defined criteria to evaluate performance of power generation technologies rather than specific energy systems (e.g. indicators such as "the share of renewable energy sources in electricity consumption" are excluded). This literature review revealed a wide set of evaluation criteria amongst a common classification adopted in this paper. Based on the various dimensions of sustainability that a technology might impact on when integrated in a specific context, criteria are categorized in the environmental dimension, technical dimension, economic dimension, and social dimension.

To further synthetize the first exhaustive set of criteria, the five guiding principles for criteria selection proposed by Wang et al. [35] – being the transparency principle, the consistency principle, independency principle, measurability principle and comparability principle – and later used by Maxim for similar purpose as in this paper [34] were consulted. Whilst consistency (consistent method through all alternatives), transparency (transparent definition) and measurability (method and data availability) of criteria must be evaluated for each criterion separately, the independency and comparability principles are character of the whole set of criteria and require statistical processing on homogenized data of the set. Data were obtained in challenging literature research, as most of the sources consulted characterized either only some of the selected technologies or used methodologies that did not fully meet the requirements of this research.
Therefore, results of several studies must be combined to expand the results of others using the original methodology or even to adapt some research methodologies to fit the aims of the current paper. For those cases of missing or inaccurate data qualitative scales and assumptions were introduced.

The independency principle avoids any overlapping of the criteria within the set [35]. Such overlapping would lead to the same aspect being counted multiple times in the final assessment and therefore distort the overall result. It is crucial to detect communalities of the definition of criteria, which, at a certain extend of communality could be combined accordingly. For example, the capital costs of a technology and the levelized costs of electricity (LCOE) produced by the respective technology are logically intertwined. In such case, the more comprehensive criteria of LCOE is seen more suitable for technology comparison. As such communalities in definition often end up in high correlation – either positive or negative for vice versa formulated criteria – statistical analysis assists in the detection of less obvious correlations than the above given example. As only monotonic relationship of two variables $\boldsymbol{x}$ and $\boldsymbol{y}$ (criteria value), and nonlinear correlations within, can be assumed for the data sets introduced in this analysis, Spearman´s rank coefficient $\boldsymbol{r_{s,xy}}$ [33] was calculated according to equation 1,

$$r_{s,xy} = 1 - \frac{6 \sum_{i=1}^{n} (x_i - y_i)^2}{n\,(n^2 - 1)} \quad (01)$$

where $\boldsymbol{n}$ is the sample size, and $\boldsymbol{x_i}$ and $\boldsymbol{y_i}$ are individual sample points. Thresholds for indicating a significant correlation are chosen to be 0.6 and -0.6, respectively [33]. For such criteria that indicated correlation above the respective thresholds, rationale, definition, and methodology were deeply investigated with the intention to uncover whether the correlation might be due to causal relations or simple historic development or even coincidence. If the assumption of causal relation was confirmed, the fewer comprehensive criteria were excluded, otherwise both criteria were retained. Appendix A includes tables for Spearman's rank coefficient and excluded criteria within each dimension of criteria.
The reduced set of evaluation criteria was further treated to test for sufficient discrimination within criteria scores enabling for differentiation of the technologies, as defined in the comparability principle [35]. Such criteria that do not vary significantly along all possible technologies but achieve approximately equal scores can be excluded from the analysis to simplify the process, as they do not impact the overall result. Therefore, coefficient of variance $\boldsymbol{C_v}$ was calculated on absolute scales of each criterion $\boldsymbol{i}$ by dividing standard deviation $\boldsymbol{\sigma_i}$ by the mean of that criteria $\boldsymbol{\eta_i}$,

$$c_{v,i} = \frac{\sigma_i}{\eta_i} \quad (02)$$

which gives a relative equivalence among the data. Technology lifetime appears to be the criterion with most equal scores amongst the technologies, resulting in a coefficient of variance of 0.31. However, this is still considered to deviate enough to include the lifetime criterion for the evaluation.

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TABLE II
FINAL SET OF CRITERIA USED FOR TECHNOLOGY EVALUATION

Dimension	Criteria	Abbreviation	Definition	Value of measure
Technical	Electrical efficiency	Eff	Ratio between output electricity and input energy.	%
	Ability to respond to demand	AtD	Ability to respond to peak demand and ensure overall grid stability in the long term.	Ranking 1 = no 2 = slow 3 = fast
	Ability to provide multiple end-use services	AtSE	Compatibility of the technology with different end uses/applications (heating, side products etc.).	Ranking 1 = none 2 = waste heat 3 = additional products
	Resource availability	RA	Direct availability of the primary energy resource.	Ranking 1 = limited resource 2 = resource available 3 = good potential 4 = very good potential 5 = independent from location
	Maturity	Mat	Stage of technology development and dissemination.	Ranking 1 = laboratory 2 = experimental/pilot 3 = confirmed 4 = consolidated
	Capacity factor	CF	Ratio of energy produced over a period of time to maximum theoretical energy that could have been produced when operated at full capacity (Load following mode is considered).	%
	Lifetime	Lt	Life expectancy of the separate technology components before significant interventions are required.	y
Economic	Levelized costs of Electricity	LCOE	Cost of electricity production over the entire lifecycle of the technology.	$/kWh
Environmental	Life cycle GHG emission	LC-GHG	GHG emissions over technology life cycle.	$gCO_{2,eq}/kWh$
	Impact on water resources	WR	Water consumption/withdrawal over the life cycle of the technology.	l/MWh
	Land use	LU	Land area modified during the lifecycle of the technology.	m^2/MWh
	Noise and visual pollution	NV	Noise pollution emitted when operating the technology and visual effects disturbing population.	Ranking 1 = significant 2 = not significant
Social	Human Health	HH	Life deterioration due to the implementation of the technology.	DALY/TWh
	Social acceptance	SA	Positive opinions related to the implementation of the technology.	%
	Job creation potential	JC	Direct employment created over the entire lifecycle of the system per installed capacity.	Ranking 1 (low) – 3 (high)

Table II summarizes the final set of criteria, including respective definition and methodology of evaluation and Table III assigns the scores obtained from literature research and qualitative assumptions considered in the MCDA.

TABLE III
FINAL SET OF CRITERIA FOR POWER GENERATION TECHNOLOGIES WITH CONSIDERED SCALES OBTAINED FROM LITERATURE AND QUALITATIVE ASSUMPTIONS

Abbreviations: BG = Biogas power, DG = Diesel generator, MHP = Micro-hydropower, MGT = Micro-gasturbine, MWT = Micro-windturbine, FC = Fuel cell, off-site generation of hydrogen (natural gas reforming), RFC = Regenerative fuel cell, on-site generation of hydrogen.

Dimension	Abbreviation	Unit	BG	DG	MHP	MGT	MWT	PV	FC	RFC	Sources
Technical	Eff	%	33	37	70	23	35	22	50	21	[34, 44, 45, 48-54]
	AtD	R 1-3	2	3	1	3	1	1	3	3	[7, 34, 38, 44, 47, 53, 55, 56]
	AtSE	R 1-3	3	2	1	2	1	1	2	3	[7, 8, 39, 57-59]
	RA	R 1-5	2	5	2	5	3	4	5	4	[48, 55, 60]
	Mat	R 1-4	2	4	3	4	3	4	2	2	[7, 34, 38, 44, 47, 53, 55, 56]
	CF	%	74	73	52	80	28	21	76	76	[34, 49, 59, 61-65]
	Lt	Y	10	10	30	20	20	20	15	15	[7, 49, 66, 67]
Economic	LCOE	$/kWh	0.15	0.46	0.15	0.31	0.28	0.31	0.26	0.5	[31, 45, 49, 55, 65 67-76]
Environmental	LC-GHG	gCO_2-eq/kWh	145	1,000	23	460	25	90	520	400	[77-88]
	WR	l/MWh	920	2,100	7	1,000	4	165	2,400	465	[78, 89-94]
	LU	m^3/MWH	170	4	2	4	4	20	4	12	[34, 87, 91, 94-97]
	NV	R 1-2	2	1	2	1	1	2	2	2	[97-99]
Social	HH	DALY/TWh	50	20	10	15	25	60	58	68	[100-103]
	SA	%	43	19	43	19	43	61	31	43	[104, 105]
	JP	R 1-3	3	1	1	1	2	3	2	5	[72, 106-108]

Notably, hydrogen to power the fuel cell receiving external supply is thought to be produced by natural gas reforming, as this process still accounts for 95% of the generated hydrogen today [10]. As data on social acceptance is scarce, the system is estimated to be only little more [57] excepted by the population, as no local emissions occur. Further, the regenerative fuel cell – even though defined as renewable technology – is also estimated to have a comparatively low acceptance, as the technology is not well known in the context.

The original data were normalized to a utility value on a dimensionless scale of 0 to 1 for within each criterion to allow for subsequent processing. Since explicitly aiming to capture any outliers, min-max normalization was applied. In this method for every criteria, the minimum value of that criteria is transformed into a 0, the maximum value gets transformed into a 1, and any other value is transformed into a decimal in between 0 and 1. The normalized value x_{norm} of original value x of criteria i is calculated by using the maximum max (x_i) and minimum min(x_i) values of the criteria span via equation 3:

$$x_{norm,i} = \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)} \quad (03)$$

For such criteria that correlate negatively with sustainability and therefore maximum value 1 would be undesirable, minuend and subtrahend in the numerator are switched.

C. Scenario Development

Even though the set of criteria defined for evaluation is as comprehensive as possible and as exhaustive as necessary, not all the criteria included might be equally important to assess the suitability of a technology. Further the technologies and settings might in future undergo potential development, influencing underlying parameter. To take account for these aspects three scenarios were developed, which shed light on respective foci. All the scenarios make use of introducing weights according to the rank-order weights approach. This weighting method implies that different weights should be attributed to the various criteria, so that $w_1 \geq w_2 \geq \ldots \geq w_n \geq 0$ with $\sum_{i=1}^{n} w_i = 1$. The different scenarios and their rationale are briefly described below.

a) Scenario 1: Strategically Important Criteria according to Expert Weights

To detect and include strategically important criteria, thereby suiting the analysis to a close-to-reality perspective, a survey has been conducted along academic experts. 68 academics, which have published relevant work on rural electrification in SSA in scientific journals within the period of 2015 to 2021 have been approached via email. The response rate was 31% with 21 valid answers on the complete survey, of from which the majority (38%) hold a professorship or work as a research associate (29%). The exact questions as well as statistics of the questionnaire can be viewed in detail in Appendix B.

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In a first step the respondent's level of familiarity with issues regarding SDG 7, minigrids and hydrogen technologies was assessed to validate the answers later on. The subsequent main questionnaire composed two major sections. At first, the respondents were asked to give their opinion on importance of the respective evaluation criteria given in Table II. As it allows for slight potential future modifications, the simple multi-attribute rating technique – extended rating (SMARTER) was adopted for this purpose. With this, the respondents were asked to place the n criteria C into an importance order: $C_1 > C_2 > \ldots > C_n$

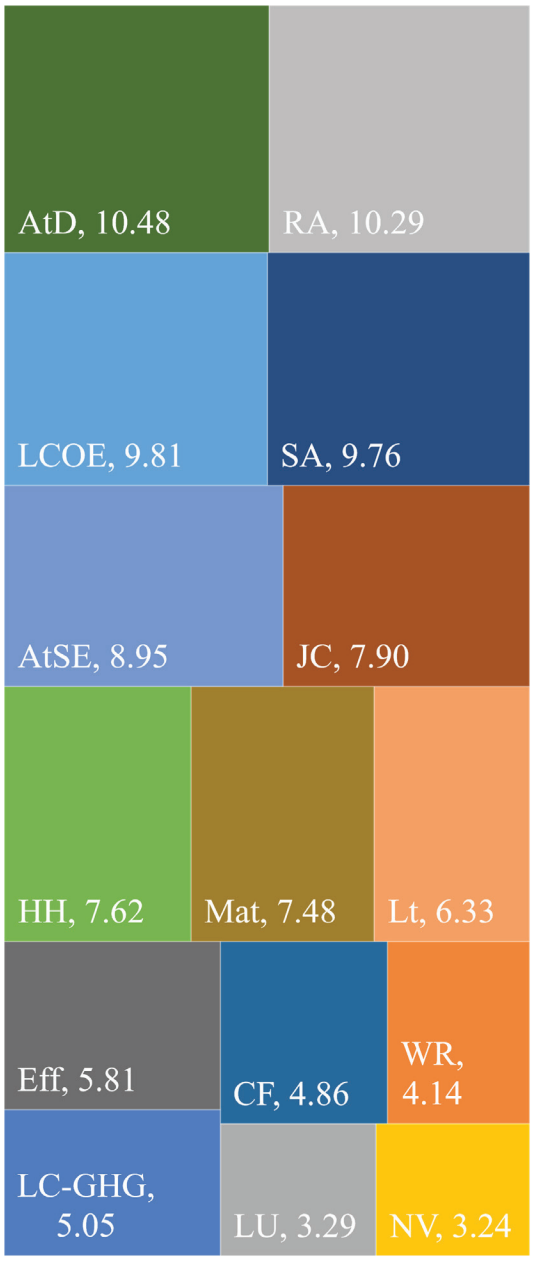

Fig. 3. Average ranking of the criteria obtained from the expert survey. LCOE = Levelized costs of electricity, HHE = Human health effect, SA = Social acceptance, JC = Job creation potential, Eff = Electrical efficiency, Mat = Maturity, DF = Capacity factor, RtD = Ability to respond to demand, AtSE = Ability to serve multiple end-uses, Lt = Lifetime, RA = Resource availability, LC-GHG = Lifecycle GHG emission, WR = Water resource use, LU = Land use, NV = Noise and visual pollution.

Figure 3 illustrates the average ranking of all criteria according to the expert survey. With the Ability to respond to Demand (AtD, 10.48) and Resource Availability (RA, 10.29), two technical criteria are estimated to be most important, just before the economic criteria of Levelized Costs of Electricity (LCOE, 9.81). Social Acceptance (SA, 9.76) and Ability to serve multiple end-uses (AtSE, 8.95) rank just behind. The impression of environmental belongings being least important compared to criteria of other dimension, are confirmed by repeating the question on estimated importance on the dimensions of sustainability. Economic dimension ranks before social and technical dimension, while environmental dimension is significantly outranked.
To specifically highlight any extreme and allow for more difference in the results, the average ranking of criteria was again normalized using min-max normalization before applying the weights to the MCDA. Table IV summarizes the applied weights.

b) Scenario 2: Market decisive criteria

The experts' assessment of decisive criteria for the choice of technology may – especially because of their academic background – suggest a fictitious optimum that does not necessarily correspond to the view of market actors, such as minigrid developers. External factors can limit a theoretically optimal choice of technology, leading to other criteria to become more important. To take such constraints into account a scenario was developed, giving more emphasis on criteria in which currently market dominating technologies are strong in – as these criteria might be reason for their market dominance.

Even though for some countries it appears to deviate, the overall picture of SSA shows the diesel generator and solar PV to hold major market shares [56, 109]. In fact, solar hybrid mini-grids are the most dominant form of modern mini-grids installed today[56], which already leads to the obvious conclusion of resource availability being restrictive factor. The normalized values of data applied in the analysis reveals the diesel generator to perform the best of all technologies in maturity – which is also associated to market availability and supply chain – ability to respond to demand and resource availability. PV also performs well in maturity, further in social acceptance, job creation potential and noise and visual pollution. Amongst the renewable energies PV has highest resource availability on the African continent [60]. With this, the scenario focuses on these criteria by increasing their weights by a factor of three. Table IV includes the weights accordingly.

c) Scenario 3: Future evolution scenario

Hydrogen technologies at the present state are at a comparatively low stage of maturity, including both technical and market related aspects. However, not only the technologies themselves might undergo future development, but also policies will affect the technologies' market environment. To take such development into account, a future scenario was constructed.
The scenario includes change in technology parameter according to prominent literature as well as emphasis on weights the authors see in alignment with the current policies. Major assumptions for this evolution scenario, taking place in 2040, are

- External hydrogen supply is assumed to be produced by large-scale water electrolysis plant with production costs of at least 1 $/kg – 2.1 $/kg [68]. Including fuel logistics and conversion the researchers assume LCOE of 0.24$/kWh [31].
- LCOE of on-site produced hydrogen are expected to fall with increased technology maturity to 0.44$/kWh [31, 68].
- Efficiencies are expected to increase for PV and hydrogen technologies by 30%.
- Improvements to reduce carbon footprint for fossil fuels can be made [51].
- Prices for renewable energies are expected to decrease by 30% as of 2040 [110].
- Impact of climate change could decrease resource availability for water resources and biomass resources.
- Fossil resources are expected to decrease, deteriorating the resource availability of diesel generator and micro-gasturbine.

According to the predominant global policy objectives, the authors assume especially such criteria to be more important in future, which are aligned with the UN SDGs. Therefore, weights are increased by a factor of two for such criteria that are explicitly linked to the rationale of SDG targets. These are Life-cycle GHG emissions (SDG 13 Climate Action), Water resource use (SDG 6 Clean Water and Sanitation), Land use (SDG 15 Life on Land), Human Health Effect (SDG 3 Good Health and Well-being), Job creation potential (SDG 8 Decent Work and Economic Growth), LCOE (SDG 7 Affordable and Clean Energy), Electrical efficiency (SDG 7 Affordable and Clean Energy) and Ability to serve multiple end-uses (SDG 12 Responsible Consumption and Production). The criterion of maturity was excluded from the analysis, as future development and respective stages of maturity remains uncertain. Further, when assuming all technologies to have reached high market maturity by 2040, the criterion would violate the comparability principle (see section B Criteria Selection). An overview of all scenario weights is given in Table IV.

TABLE IV
SUMMARY OF WEIGHTS APPLIED ACCORDING TO THE DIFFERENT SCENARIOS

LCOE = Levelized costs of electricity, HHE = Human health effect, SA = Social acceptance, JC = Job creation potential, Eff = Electrical efficiency, Mat = Maturity, DF = Capacity factor, RtD = Ability to respond to demand, AtSE = Ability to serve multiple end-uses, Lt = Lifetime, RA = Resource availability, LC-GHG = Lifecycle GHG emission, WR = Water resource use, LU = Land use, NV = Noise and visual pollution.

	LC-GHG	WR	LU	NV	LCOE	HH	SA	JC	Eff	Mat	CF	AtD	AtSE	LT	RA
Expert weights	0.25	0.125	0.007	0	0.91	0.6	0.9	0.64	0.36	0.59	0.2	1	0.79	0.43	0.97
Market dominant	1	1	1	3	1	1	3	3	1	3	1	3	1	1	3
Future 2040	2	2	2	1	2	2	1	2	2	0	1	1	2	1	1

D. MCDA Ranking

Applying the weights to the criteria results in an overall ranking of the technologies. Popular weighted arithmetic mean (WAM) method was chosen for aggregation, which calculates the weighted average x_{wa} with the weights w_i applied to criteria values x_i by equation 4

$$x_{wa} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \quad (04)$$

In energy related research most common method is to apply equal weights [35], which was adopted for this paper to serve as reference point for the different scenarios to compare with.

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III. RESULTS

A. Strengths and Weaknesses of Fuel Cells

First results and implications from the analysis can already be drawn from observing the normalized scores of the fuel cell within the different evaluation criteria. These normalized scores indicate the relative performance of the technologies in the respective discipline compared to the alternative technologies. Figure 4 illustrates this performance disaggregated for the fuel cell powered by hydrogen from external natural gas reforming, and the regenerative fuel cell, which generates hydrogen on-site assuming the best renewable primary power source in each criterion. The graph reads that above the abscissa is the relative positive deviation from the average of the technologies in the respective criterion. Conversely bars below the abscissa indicate a deviation to the negative. The height of the bars quantifies the relative distance from the average. If the bars meet the respective dashed lines, it implies that the technology in the considered categories performs best – for those bars that are above the abscissa – or performs worst – for those bars that are below the abscissa.

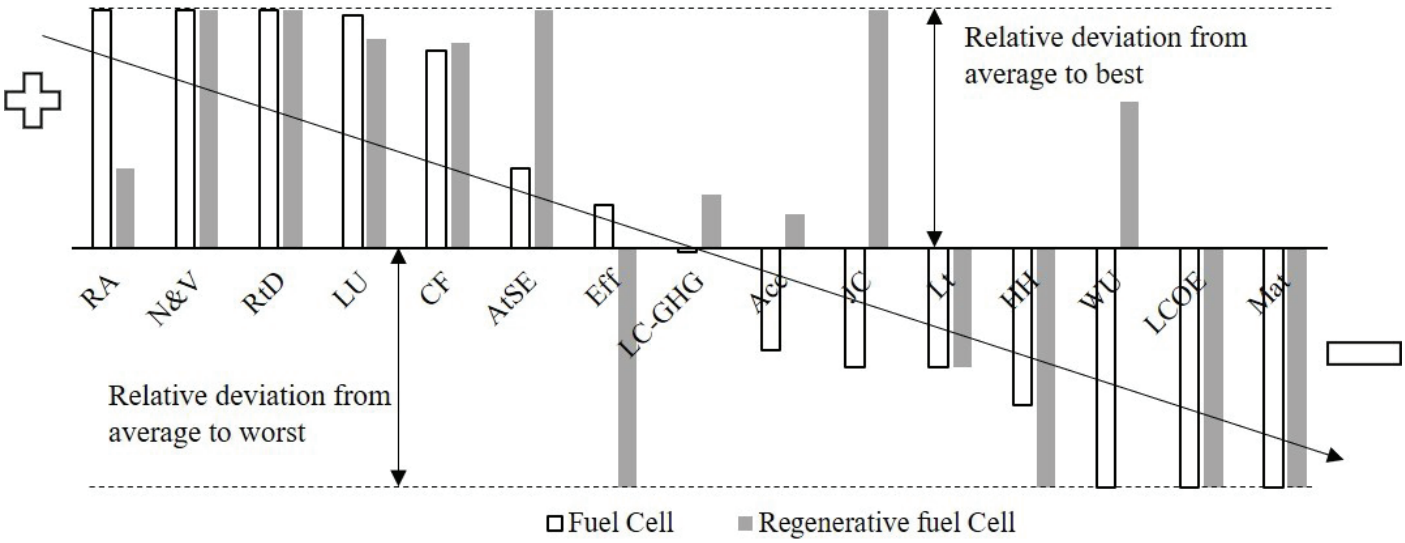

Fig. 4 Relative performance of the fuel cell and regenerative fuel cell in respective criteria.
LCOE = Levelized costs of electricity, HHE = Human health effect, SA = Social acceptance, JC = Job creation potential, Eff = Electrical efficiency, Mat = Maturity, DF = Capacity factor, RtD = Ability to respond to demand, AtsE = Ability to serve multiple end-uses, Lt = Lifetime, RA = Resource availability, LC-GHG = Lifecycle GHG emission, WR = Water resource use, LU = Land use, NV = Noise and visual pollution

The figure indicates that both options of fuel cells are least mature and have the highest LCOE, which summarizes overall economic performance in the study. Also, both alternatives perform comparatively low in the effect on human health. This is due to the fact that hydrogen technologies require a significant amount of raw materials, whose mining processes are potentially harmful to health. As the paper covers for – in this sense – the worst case of on-site production of hydrogen, a separate electrolyzer and fuel cell summarized as regenerative fuel cell performs even worse than a stand-alone fuel cell in this discipline.
In contrast to any other renewable power generation technologies, the results indicate that both fuel cell integration topologies have the highest possibility to respond to demand, as fuel cells can operate dynamically [7, 44]. Resource availability of natural to fuel the stand-alone fuel cell is still assumed to be without major risks by now. The resource availability of the on-site produced hydrogen depends on the best available renewable primary electricity source.

B. Technology Ranking

As a common practice to present results of MCDA, Figure 5 illustrates a ranking of the technologies. The figure plots the normalized and weighted aggregated values of all criteria applied in the analysis. The ranking was performed for each of the beforementioned scenarios of: 1. weights according to the expert survey (grey bars), 2. weights increased for criteria decisive for market penetration (market decisive criteria) (crosshatched bars) and 3. parameter and weights adjusted according to estimated future development (black bars). To allow for better comparison and discussion, the blank bars illustrate the ranking when applying equal weights to all criteria.

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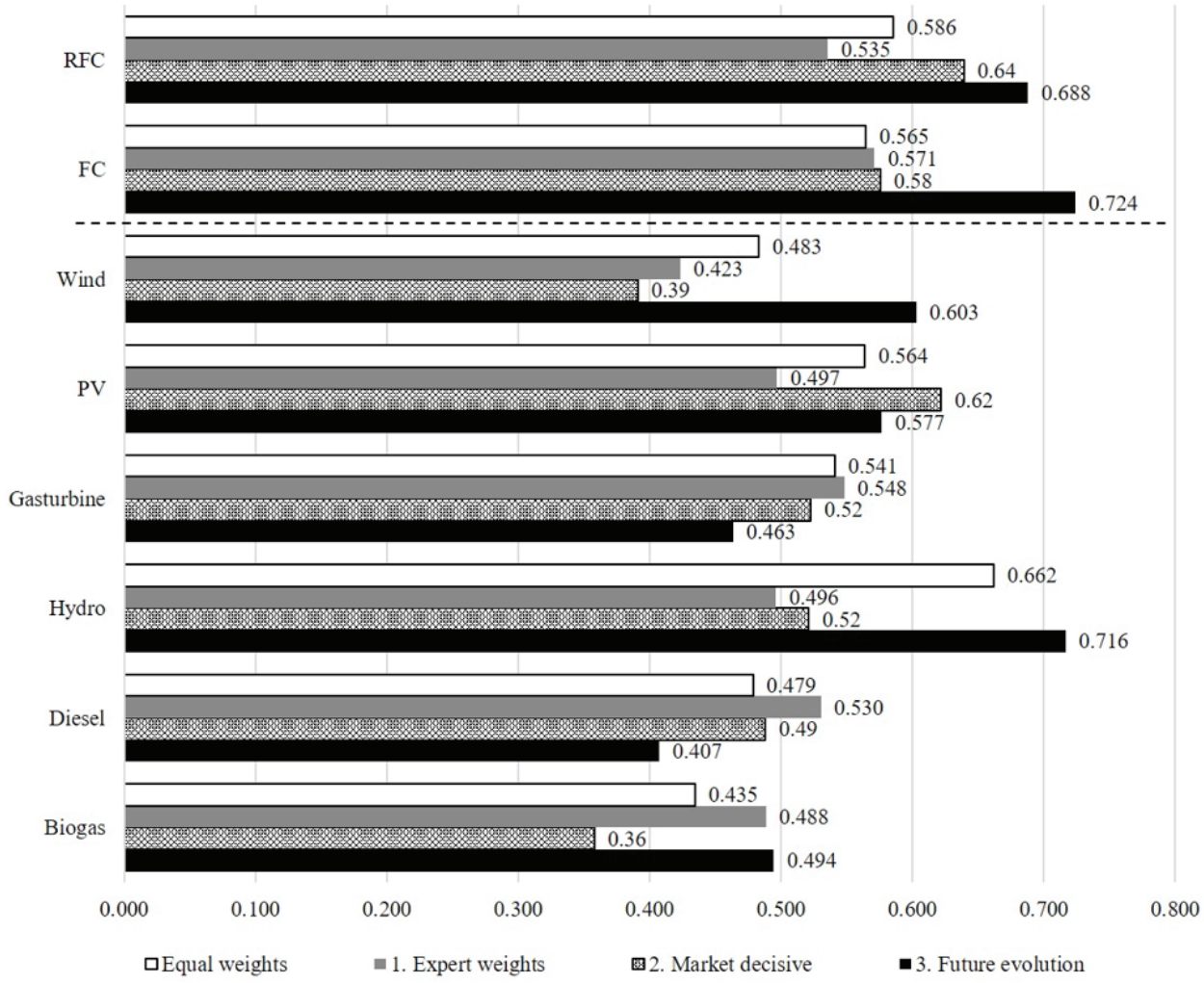

Fig. 5 Sustainability ranking of the power generation technologies for applying equal weights and applying the predefined scenarios.

Scenario 1: strategically important criteria: expert weights
Applying weights according to allocation of the consulted academic experts, as explained in the methods section, results in the fuel cell supplied with external produced hydrogen from natural gas reforming to rank first (0.571). The next most suitable power generation technologies for rural minigrids according to the analysis are micro-gasturbine (0.548), the regenerative fuel cell producing hydrogen on-site (0.535) and the diesel generator (0.53). Established renewable technologies rank behind the fossil competitors, with PV (0.497) and micro-hydropower (0.496) ranking before biogas power (0.488) and the least suitable technology of micro-windpower (0.423).

Scenario 2: market decisive criteria
Shifting weights towards such criteria being decisive for high market shares today ranks the regenerative fuel cell (0.64) just before PV (0.62). The stand-alone fuel cell improves slightly compared to an equal weight scenario, leveling on third place (0.58) just before micro-gasturbine and micro-hydropower (both 0.52). Biogas-power ends up in the last place (0.36).

Scenario 3: future evolution
According to the future scenario with parameter and weights applied to estimated future development, the stand-alone fuel cell – notably powered by hydrogen from large scale water electrolysis in this scenario – is the most suitable technology for power supply in rural minigrids (0.724). The fuel cell is closely followed by micro-hydro power (0.716) and the decentralized regenerative fuel cell (0.688). Fossil fuel-based technologies micro-gasturbine (0.463) and diesel generator (0.407) are significantly outranked by renewable power generation technologies.

IV. DISCUSSION

The discussion will at first deepen the results of the technology ranking with paying particular attention to the performance of hydrogen technologies. Subsequently extracts of the expert survey will be presented to include some prominent points of discussion regarding the application of hydrogen in SSA minigrids.
Against previous studies, which only considered economic performance of technologies (a.o. [27]), this MCDA analysis indicates that hydrogen technologies are highly suitable for power supply in SSA minigrids. Both studied alternative systems, the stand-alone fuel cell supplied with external produced hydrogen and the system considering on-site generation of hydrogen, rank among the top three technologies in each defined scenario.
In the first scenario weights were applied according to the suggestions of academic experts. With this, the weights have relatively increased especially for the ability to respond to demand, resource availability, LCOE, social acceptance and the ability to serve multiple end-uses. The two first mentioned and thereby most important criteria are especially met by fossil fuel-based technologies, but also the stand-alone fuel cell supplied by hydrogen from natural gas reforming, which conclusively benefits from increasing the weights. Also, LCOE of this fuel cell topology (0.26$/kWh) is competitive to other technologies, while social acceptance is assumed to be only slightly higher than the already biased fossil technologies, e.g. diesel generator.
Considering the on-site generation of hydrogen however, the ability to respond to demand is not affected and still at maximum of the applied scale. However, resource availability deteriorates compared to fossil fuels and LCOE increases significantly. As the weights for these criteria have increased, the aggregated score of the reversible fuel cell decreases. Neither the social acceptance – estimated to be lower than other renewables, as the fuel cell technology in general is not very well known – nor the outstanding ability to provide multiple end-uses can compensate for the losses. However, the latter must be emphasized, as it can become a strategically important capability in the future.
As e.g. Topriska et al. [8, 111] proposed in previous studies, the usage of on-site produced hydrogen as clean cooking fuel is technically viable and can cause major benefits to the users, especially concerning health. Still facing a huge gap in the aim to provide clean cooking fuels to all people by 2030 in SSA [3], the expanded usage of hydrogen not only for power generation but also as cooking fuel must be investigated for possible synergies in subsequent work.

Additional finding of the scenario is that other renewable technologies are not suitable without additional storage components. Especially the important criteria of resource availability and ability to respond to demand are not reflected by the stand-alone systems.
However, for all previous discussions it must be noted that the indications of the experts on strategically important criteria can be assumed to be neutral – as the vast majority of 72% is employed at an academic institution – but also might not reflect the opinion of actual minigrid deployer and investors.

To overcome this potential limitation, the second scenario sheds light on such criteria in which current market dominating PV and diesel generator perform best in. These include maturity, ability to respond to demand, resource availability, social acceptance, job creation potential and noise and visual pollution. Not surprisingly, the results demonstrate a strong position of PV in comparison to other technologies. Notably, the regenerative fuel cell system border includes an upstream renewable power generation technology, as explained in the material and methods section. Therefore, advantages of PV in this scenario are also reflected by this system topology, which ends-up slightly before PV. However, also the stand-alone fuel cell ranks among the top-three in this weighting scenario, as again ability to respond to demand and resource availability appear to be decisive.
As with this both technologies perform well in the ranking not only when applying weights according to impartial academic experts but also when emphasizing criteria decisive for actual market share, the results from the MCDA suggests that hydrogen technologies are indeed suitable for rural minigrids and competitive to other technologies.

The MCDA results from applying parameter and weights according to the future scenario, which notably includes the stand-alone fuel cell to be supplied from large scale water electrolysis plants, indicate the future potential of such technologies. As such large-scale production of hydrogen has the potential to reduce LCOE significantly, benefitting from the economy of scale effects, the stand-alone system outranks the on-site production of hydrogen.
As an aside, from this future scenario it must be noted that micro-hydropower significantly improves in the ranking from applying future parameter and weights according to sustainable development policies. This result supports the estimation of the SE4All initiative which suggests micro-hydropower to be an emerging technology for future minigrid development also in SSA [56].
In contrast to the indications of the MCDA findings, the consulted experts of the survey in general are not convinced that fuel cells play a major role to supply power to rural SSA minigrids in future. The question on "What is the likelihood that hydrogen

technologies will find application in rural minigrids as a widespread solution in the future?" was answered with "Not very likely, but possible" by a slight majority of 57%. However, only 16% of the respondents answer the same question with "Very likely". Major concerns of the experts refer to low technology maturity and economic performance. This supports the impression that financial aspects and supply-chain issues are still most important for actual market penetration of a technology. As the first point of criticism – maturity – is only ranked 8th on average as most decisive criteria for minigrid technologies in the expert survey (compared to Figure 3), this effect is not very much represented in the results from scenario 1.

The latter however – low economic performance – is supported by the considerations for the on-site production of hydrogen especially. However, assuming only the fuel cell to be decentralized while hydrogen production takes place in large scale water electrolysis plants – as considered in scenario 3 –, the technologies could become cost competitive. Nevertheless, as the development of such large-scale plants involve substantial financial investment and political support, this development is not likely to be in hands of minigrid developers. The authors rather suggest investigating economic niches for decentralized hydrogen production – such as local phenomena of excess electricity – and improvements in system integration in future work. Also, potential benefits from fuel flexibility and connections to other sectors, both of which stated as major benefits by the consulted experts, should be followed. For the extensive set of comments given by the experts see Appendix B.

V. CONCLUSIONS

The study aimed to provide a comprehensive sustainability assessment of fuel cells and a set of power generating technologies in rural SSA minigrids, using multi-criteria decision analysis. The approach – opposed to previous works – opens the discussion on the fit of hydrogen technologies for this purpose to include not only economic or technical concerns but also social and environmental aspects which a technology touches on in electrification. The development of different scenarios additionally sheds light on: 1. strategically important criteria according to academic expert estimations, 2.

criteria decisive for actual market penetration of power generation technologies in minigrids and 3. future parameter and criteria in alliance with sustainable development.
The findings indicate the fuel cell to be highly suitable for rural power generation in SSA minigrids. In each scenario both considered fuel cell integration alternatives of on-site and off-site generation of hydrogen rank amongst the top three technologies. Findings of the last scenario suggest the large-scale electrolysis and supply of decentralized fuel cells to be advantageous against decentralized production, as the LCOE can be decreased. However, as this is neither in hands of minigrid developers nor foreseeable in near future, economic niches and use-cases for decentralized production must be defined. Findings from the MCDA and comments given by academic experts in a survey suggest such objects of investigation to be local phenomena, such as excess electricity, expanded usage of hydrogen on other sectors with associated business models and flexible fuel usage.

On the mission to close the gap for rural electrification until 2030, it is important to already create long lasting sustainable solutions and avoid any extensive future modifications of energy systems. Therefore, energy system developer must think the systems with perspective on potential future development of the people and region of concern, leaving no future limitations for the user. Considering electricity supply, for Solar Home Systems, this implies to study a future interconnection of the single appliances to a "swarm" [112]. First studies on this system design promise to increase the reliability of supply and decrease overall LCOE [112]. For minigrids deployed today it means to already consider future grid connection, leaving the challenge to design the system appropriately that it is of value still, "when the grid arrives". Additionally, considering other needs of the people and region of concern, energy system decision maker should integrate possible solutions out of the various fields of human development in the energy system planning process. This may include other energy vectors, such as clean cooking or transportation services but also non-energy related topics such as food supply. Previous works have extensively shown the various (positive and negative) interlinkages of SDG7 and other fields of development (a.o. [33, 113]). Such studies must find their way into energy system planning to create sustainable and impactful energy supply, beyond the SDG period.

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COMPETING INTERESTS
The authors declare that they have no competing interests.

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APPENDIX

Appendix A: Spearman´s rank coefficient of initial set of criteria

TABLE A.1
SPEARMAN'S RANK COEFFICIENT FOR CRITERIA OF THE TECHNICAL DIMENSION. EXCLUDED FROM THE SET ARE ENERGY EFFICIENCY, INFRASTRUCTURE FKEXIBILITY, WEATHER AND CLIMATE DEPENDENCY< DEPENDENCY ON FOSSIL FUELS.

Spearman's Correlations											
Variable		**Electrical efficiency.**	**Energy efficiency**	**Ability to respond to demand**	**Ability to provide multiple end-use services**	**Infrastructure flexibility**	**Weather and climatic condition dependence**	**Resource availability**	**Maturity**	**Capacity factor**	**Lifetime**	**Dependence on fossil fuel**
1. Electrical efficiency.	Spearman's rho	—										
2. Energy efficiency	Spearman's rho	0.164	—									
3. Ability to respond to demand	Spearman's rho	-0.154	0.432	—								
4. Ability to provide multiple end-use services	Spearman's rho	-0.170	0.539	0.776	—							
5. Infrastructure flexibility	Spearman's rho	-0.179	-0.548	-0.473	-0.843	—						
6. Weather and climatic condition dependence	Spearman's rho	0.189	0.674	0.816	0.500	-0.264	—					
7. Resource availability	Spearman's rho	-0.385	-0.131	0.674	0.136	0.297	0.534	—				
8. Maturity	Spearman's rho	-0.208	-0.250	0.041	-0.500	0.843	0.250	0.690	—			
9. Capacity factor	Spearman's rho	-0.143	0.764	0.849	0.794	-0.657	0.756	0.330	-0.227	—		
10. Lifetime	Spearman's rho	0.131	-0.210	-0.566	-0.852	0.668	-0.248	-0.096	0.406	-0.412	—	
11. Dependence on fossil fuel	Spearman's rho	0.000	-0.322	-0.683	-0.167	-0.176	-0.837	-0.813	-0.669	-0.474	0.083	—

TABLE A.2

SPEARMAN"S RANK COEFFICIENT FOR CRITERIA OF THE ECONOMIC DIMENSION. EXCLUDED FROM THE SET ARE INVESTMENT COSTS AND LCOE DO NOT EXCEED THE THREASHOLD OF 0.6, BUT AR INTERWINED BY THEIR DEFINITIN

Variable	LCOE	Invest	O&M	Fuel
1. LCOE	—			
2. Invest	-0.468	—		
3. O&M	-0.673	0.847	—	
4. Fuel	0.748	-0.809	-0.668	—

TABLE A.3

SPEARMAN'S RANK COEFFICIENT FOR CRITERIA OF THE ENVIRONMENTAL DIMENSION. EXCLUDED FROM THE SET ARE LOCAL GHG EMISSION, RENEWABLE ENERGY.

Variable	Local GHG emissions	Life cycle GHG emission	Renewable Resource	Impact on water resources	Land use	Noise & visual pollution
1. Local GHG emissions	—					
2. Life cycle GHG emission	0.802	—				
3. Renewable Resource	-0.986	-0.791	—			
4. Impact on water resources	0.802	0.929	-0.791	—		
5. Land use	-0.324	0.185	0.328	0.185	—	
6. Noise & visual pollution	-0.540	-0.433	0.548	-0.433	0.000	—

TABLE A.4

SPEARMAN'S RANK COEFFICIENT FOR CRITERIA OF THE SOCIAL DIMENSION. EXCLUDED FROM THE SET IS EXTERNAL SUPPU RISK.

Variable	Job creation potential	External supply risk	Social acceptability	Human Health
1. Job creation potential	—			
2. External supply risk	0.669	—		
3. Social acceptability	0.769	0.882	—	
4. Human Health	0.869	0.474	0.657	—

Appendix B: **Questionnaire composition and response statistics**

Valid answers: 21 (30.9% response rate)

Section 1: Introduction

- How familiar are you with the issues concerning the electrification via minigrids?

Options: Rank from "not familiar at all" to "expert" on a 5-step scale.

1. Technologies for rural electrification: 1= 4.8%, 2 = 4.8%, 3 = 14.3%, 4 = 42.9%, 5 = 33.3%
2. Relation of access to electricity and development: 1= 0%, 2 = 4.8%, 3 = 14.3%, 4 = 57.1%, 5 = 23.8%
3. Sustainable Development Goal no. 7: 1= 7.8%, 2 = 4.8%, 3 = 28.6%, 4 = 38.1%, 5 = 23.8%
4. Multi-Tier framework for energy access: 1= 9.5%, 2 = 19.0%, 3 = 23.8%, 4 = 33.3%, 5 = 14.3%

Section 2: Research type technologies

- We would like you to choose the order of importance for technical, social, environmental and economic aspects of sustainable electrification through minigrids. Please order it depending on the importance you think it has from (1 – most important to 4 – least important).

Options: "Technical dimension", "Social dimension", "Environmental dimension", "Economic dimension".
Average ranking: Technical dimension 2.7, Social dimension 2.3, Environmental dimension 3, Economic dimension 2.0.

- We would like you to choose the order of importance for the following sustainability criteria in sustainable electrification through minigrids. Please order it depending on the importance you think it has from (1 – most important to 15 – least important).

Options: See Table 4. Results see Figure 6.

Section 3: Research type focus hydrogen

- In your opinion, what is the likelihood that hydrogen technologies will find application in rural minigrids as a widespread solution in the future?

Options: "Not likely at all" (5%), "Not very likely, but possible" (57%), "Indifferent" (19%), "Very likely" (14%), "No doubt at all" (0%).

- What obstacles do you see for hydrogen technologies to become a future solution in minigrids?

Options: Free text. Answers: see Table 11.

- What are the strengths that you see for hydrogen technologies to become a future solution in minigrids?

Options: Free text. Answers: see Table 11.

TABLE B.1

SURVEY RESPONDENT's COMMENTS ON OBSTACLES (LEFT) AND POTENTIAL (RIGHT) OF HYDROGEN TECHNOLOGIES IN RURAL MINIGRIDS.

What obstacles do you see for hydrogen technologies to become a future solution in minigrids?	**What are the strengths that you see for hydrogen technologies to become a future solution in minigrids?**
Supply chain and infrastructure. Usually MG are very remote. Renewable Energy should be easier and cheaper.	A green alternative compared to Diesel or gas, but with the same advantages for flexibility and disadvantages for logistics and price.
I think in Africa, this technology is not well considered by the authorities.	Flexibility and efficiency
Technological maturation is not sufficient for hydrogen technologies, yet. Also, not many communities/organizations are familiar with the technology.	The emissions of hydrogen technologies, and their land and water resource usages are relatively lower than the existing technologies.
Late comer	Resource flexibility
Costs, maturity / availability of technology; developers were hesitant to use Li-Ion instead of L/A batteries because of lack of field experience with the "new" technology. This will also happen to H2.	Seasonal storage and connection to other sectors. but both strengths do not really apply for mini-grids for electrification (no seasonal variation in solar irradiation, no industrial H2 demands).
-Fuel cell and electrolyser option - currently too expensive with low round-trip efficiency, and small scale primary power hydrogen technologies are also less likely to get attention than larger scale hydrogen technologies. -Other storage technologies may reach maturity first even if not fundamentally better suited - flow batteries or simply much cheaper conventional chemical batteries, e.g. -Greenhouse gas emission reduction goals not being a high priority for developing countries - therefore the diesel is more attractive -Public perception: New technology largely unproven in African mini-grid context - several pilot rural minigrid projects have already failed (South Africa as example) -Additional complexity of system with additional integration aspects - limited knowhow of maintenance and installation etc. Electrolysis would also require distilled water supply	-Long term seasonal storage potentially allowing 100% renewable energy systems. -Cogeneration to recover heat losses -Possibility of replacing existing diesel generators with hydrogen -Centralized "green fuels" created from hydrogen and transported to be used to replace diesel could have very interesting applications if made economically viable -"Clean" with low or zero noise -Global focus on hydrogen tech for net-zero etc. could have spillover effects making hydrogen tech better universally and therefore better for rural electrification etc.
I don't think one would find the necessary capacities in Africa for operation and maintenance. Also, storage systems are not the main bottleneck of current minigrid projects, which often fail for other reasons.	
-cost (short term) -technology -awareness -acceptance -safety	-cost (long term) -power capacity

Hydrogen technology (I mean green technology) is neither a mature nor a cost-effective solution for developed countries. So, I think it is not a suitable solution for rural minigrids in developing countries in the next immediate future.	
Technology not mature enough even for OECD countries, while blue hydrogen is not a sustainable solution even for OECD countries, blue hydrogen is suitable only when large abundancy of supply, and is ment for long distance transport of energy. Situations that do not occur in rural minigrids.	-Could become a seasonal storage for minigrids outside the tropical band who experience strong resource availability seasonal variations. -In cases with huge abundancy of (solar) resource could become a source of income for the village (a good to trade or sell).
-The technology is yet to be mature and research is still ongoing. The cost of settings up hydrogen based technology is high now and may be like that for the decade to come. -Unless strong commitment are made and more funding is given for Research & Development and large scale deveplopment to drive down cost.	-One of the key challenges in minigrids today is the storage given the intermittency of renewable and high cost of batteries even though is being made. -In this position Hydrogen will drastically change the future of minigrids. - Hydrogen could play a significant role as an alternative to store excess production from RE and available when needed.
-If we consider the economic status of most African countries, the initial investment cost would be a challenge for the Governments to swiftly adopt hydrogen technologies.	Clean , reliable and Sustainable
Still not enough tested for rural applications, so it's hard to identify its potential.	It could be an alternative source where other resources (mainly sun, wind and hydro) are scarce.
Transportation and storage	High energy density

Section 4: Sociodemographic

- Profession: What is your current position?

Options: "Student in a bachelor's degree program" (0%), "Student in a master's degree program" (0%), "Research associate at a university or research institute" (29%), "Postdoc at a university or research institute" (5%), "Professor at a university or research institute" (38%), "Employed in the industry" (10%), "Other" (14%)

- Academic background: What is your academic background?

Options: "Economics" (24%), "Engineering" (67%), "Sociology" (0%), "Natural Sciences" (5%), "Other" (0%)

- Gender: What is your gender?

Options: "female" 23.8%, "male" 71.4%, "other" 0%, not stated: 4.8%.

- Age: How old are you?

Options: "younger than 20 years old" 0%, "20 to 30 years old" 28.6%, "30 to 40 years old" 42.6%, "40 to 50 years old" 19.0%, "50 – 60 years old" 0%, "60 – 70 years old" 4.76%, "70 years or older" 0%, not stated: 4.76%.

- Which is the country, where you are currently living?

Options: See World bank list of countries.

Answers: Spain (2), Germany (4), United States (2), Algeria (1), Canada (1), Japan (1), South Africa (1), Italia (3), Benin (1), Sierra Leone (1), Malaysia (1), Not answered (3)

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