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Arab Academy for Science, Technology, and Maritime Transport, AASTMT Abu Kir Campus, Alexandria, EGYPT
P.O. Box: Miami 1029
Tel: (+203) 5622366/88 – EXT 1069 and (+203) 5611818
Fax: (+203) 5611818
Web Site: http://apc.aast.edu

RESD Journal of Renewable Energy and Sustainable Development

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The role of a "Civic University" in the frame of Quadruple Helix approach to development
The paradigm of MED-QUAD project

Anna Tozzi

Professor in Geometry, University of L'Aquila
anna.tozzi@univaq.it

Societies are witnessing profound changes and coping with a great variety of challenges, both foreseen and unexpected, for which are not fully prepared. The transformations at environmental, scientific, technological, cultural and social level force everyone to rethink the meaning and even the value of the human experience and urge the academic community, policymakers and decision-makers within higher education and wider society to find proper solutions.
Universities are at the center of this transformation process with their dual responsibilities at local and global scale, coping with the intrinsic difficulties in addressing local and global demands to contribute to a more equitable and sustainable society.
More and more, higher education sector is required to play as a social agent by exploiting the multiplicity of its knowledges as well as exploring teaching methodologies, curricula and the concept of lifelong learning.
Universities must analyse and interpret the current concept of university social engagement and social responsibility and reflect on how "glocal" engagement should be included in teaching, learning, research and institutional activities, governance and leadership. They should identify how the different social actors are involved in glocal engagement practices, and how they can interact with them.
MED-QUAD project provides an example of university civic engagement in the Mediterranean region, including EU (IT and GR) and non-EU institutions (EG, TN, JO, PA).

1. The "Civic University"

Originally Universities were embedded in the cultural and economic life of the cities everywhere in the world. In the 19th century they were required to support industrialisation by providing scientific advice and skilled labour, but, through the organisation of medical schools and hospitals, they contributed also to improve the health and well-being of the population.
Gradually, during the 20th century, a changed policy concerning the higher education systems with an increasing central governmental support, produced a disconnection of universities from the places in which they were located.
In the last 20 years, crisis and challenges of any kind, are forcing universities to revise their role and to reconnect with their Cities, namely, to "re-invent the civic university" [3].
This means delivering benefits to society as a whole: local, regional, national, global by rediscovering the role of "anchor institution" in place making, innovation, economic and social development.
But realizing the potential of a civic university does not depend only on what the university does, but also on the capacity of its city partners in the public and private sector.
For a university, being anchored in a specific territory, requires, in one side, the identification of the academic practices that are relevant to the place where academics live and work as citizens, and on the other side, the solutions of the problems faced by the communities where they belong, by playing their role of repository and producers of that multidisciplinary knowledge necessary for coping with the increasingly complex challenges faced by the global society.
On the other hand, Cities are increasingly becoming direct responsible for the local economy, for the well-being and education of their citizens, for the environmental and cultural heritage preservation and enhancement.
Cities and universities should set priorities jointly and work together to achieve them with the awareness that this new approach benefits both sides. Thus, the city engagement, for the civic university, represents also an opportunity for exploring new research methods and fields and stimulating the creative potential of its academic community [6]. A civic university is characterized by its ability to integrate its teaching, research and engagement missions with the outside world without reducing their quality.
In this renovated scenario, universities and city partners must work in new ways: Higher Education

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provides intellectual and human capital for the city, public sector develops coherent policies linking territorial development to innovation and higher education, private sector invests in people and ideas for creating growth.
For achieving these goals new methods are needed. Concepts such as "Quadruple Helix", social innovation and living laboratories are some new tools for a multi-inter-disciplinary and trans-partner working, fundamental for addressing the new societal challenges.

2. The new paradigm

The Quadruple Helix (QH) model of development integrates to the three pillars: research, industry, government, the "civil society" so as to provide additional perspectives to the (territorial) innovation ecosystem, where all stakeholders are active players in jointly experimenting new ways of doing things and creating new services and products.
Thus, the QH approach integrates the social component to the previous Triple Helix (TH) model where the three components, Universities, Enterprises and Governments, cooperate on the base of the existing University/Enterprise, University/Governments, Enterprise/government relations, focusing on one or another of the bilateral cooperation. Indeed, TH model is based on the "Knowledge Triangle": Education-Research-Innovation that, focused on the concept of knowledge economy, proved to be not sufficient to support development and innovation.

QH model moves towards the concept of knowledge society/democracy with the addition of a fourth sphere.
This swift reinforces the role of universities as Civic Universities in the implementation of their third/fourth mission.
Indeed, including "civil society" means considering (among others):
- Citizens, as users requiring new services and products: user-driven innovation
- Culture-based and media-based public, providing multiculturalism and creativity in hard and soft sciences: multi xxxx(local/national/global)-level innovation
- External scientific experts, as advisors for governments: research/industry-driven innovation
- Non-profit organisations, as patterns for combination of public/private funding
- Arts and artistic research, as a new form of knowledge creation.

Thus, a Quadruple Helix approach to science, research and innovation that embraces university, business, government and civil society within the City, requires a changing process in the functions of the four components, with the awareness that these "four helices", by joining forces, will be able to align goals, amplify resources, mitigate risk and accelerate progress. However, in order to cooperate, the four components, need to find or better, to build up, a place (living labs, co-working places) where they can discuss the problems and propose the possible solutions as well as a methodology for implementing the activities identified as those capable to stimulate and exploit the innovation potential.

There is not a unique recipe to establish a QH development model. The methods and tools must be carefully chosen according to the several variables that characterize the territory and its university.
The QH model proposed by MED-QUAD project, offers a huge opportunity, but the 4 components need to acquire competences for exploiting the capacity of ICT to stimulate long-run endogenous economic growth.
The concrete activities outlined in the project, will adopt the twelve principles of Open Innovation 2.0 that clearly highlight how SMEs, in order to survive, need to establish trusted relations to the other components, by means arrangements that may be implicit (trust culture) or explicit (formal contracts), but in any case resulting from a people-to-people cooperation [1].

Concerned territory – as well as the Digital Economy - is characterized by small and very small sized companies, so Open Innovation 2.0, mainly discussed in large-scale companies, is not fully suitable. Thus, in order to create the right environment for a balanced and equally committed cooperation among the 4 helices, the project will adopt the "Embedded Innovation 3.0" paradigm, where the notion of "embeddedness" is introduced to mark the increasing challenge of integrating firms into their surrounding communities to assure the absorption of their exploitable knowledge [7,8].

The main actors are the universities which will improve their capacity to be and act as "Civic Universities" in strict cooperation with the cities of which they are part as "anchor" Institutions [5,6] together with the socio-economic stakeholders and the citizens, who all will learn how to contribute in local planning processes and in shaping the local economies.
The project entails organisational innovation, not only as supporting factor for product and process, but also as tool for improvement of firms' ability to learn and utilize new knowledge and technologies through a wise management of external relations, according to Oslo Manual (2005).

The first innovative approach proposed by MED-QUAD is the use of new organizational methods in the firm's relations with research institutions, (local) government and society.
The aim is to create an environment where the key actors cooperate for coping with the limitations of the "technological paradigm" designed by Ranga and

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Etzkowitz (2013) for the Triple Helix Model [2], since in the region the knowledge space scarsely takes advantage of universities focused on applied sciences, and the consensus space suffers from a sound institutional support.
The project intends to add a societal perspective in such a manner that the systematic way of pursuing research/technology-driven innovations (TH), will be shifted to a systematic way of pursuing demand- or user-oriented innovation (QH).

The MED-QUAD project expected results can be classified in three main categories:

1. Innovative approaches, strategies and tools for the creation of a proper innovation ecosystem that, tailored on the specific characteristics of each territory, is able to boost innovation,
2. Methodologies and means for enhancing competencies, capacities and skills of decision and policy makers in the local and national governmental departments in charge of territorial and economic development,
3. Concrete examples of methodologies and tools application.

In the first category there is the proposed QH model that integrates different approaches:
User-centered (TH+users), Firm/University-centered and Public/Firm-centered, aimed at enhancing in an interconnected way social inclusion, user centrality, creativity and public services.
This integration makes the model interdisciplinary and trans-disciplinary encompassing the whole disciplinary spectrum, thus going beyond the Quintuple Helix model where the inclusion of the environment as fifth helix is not sufficient to ensure the achievement of the UN Sustainable Development Goals.
In the second category there are the Training activities and the Thematic Seminars aiming to provide new indicators for measuring innovation.
In the third category there are the two cross-border Living Labs and the City co-working spaces where real life problems are analysed and solved.
All of them are sustainable and replicable and provide suitable and efficient tools for addressing the development priorities of Universities, Governments, Enterprises and Citizens.

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About Prof. Anna Tozzi

Education and training:
1970: Master Degree in Mathematics

Relevant Professional Experience:
1970--1973: Research fellow CNR (National Research Council)
1974--1983: Assistant Professor, University of L’Aquila
Tasks: Research and teaching courses of Topology, and General Mathematics
Since 1984: Professor in Geometry, University of L’Aquila

Teaching activities:
Topology, Algebraic Topology, Mathematical Logic, Geometry and Linear Algebra

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Research Activities:

1998-2000&2000-2002:	Coordinator of local Unit of the National Research Project-PRIN "Constructive Methods in Topology,Algebra and Programme Analysis"
2002-2004 & 2004-2006:	Coordinator of local Unit of the National Research Project-PRIN "Constructive Methods in Topology, Algebra and Information Technology"
2008 - 2010:	Member of the Research Unit of Padua University for the National Research Project-PRIN "Constructive Methods in Topology, Algebra and Information Technology"
2012 - 2014:	Member of the Research Unit of Padua University for the National Research Project-PRIN "Logical Methods of Information Management"
1994 - 2010:	Organiser and scientific responsible of several Scientific Seminars and 5 International Conferences on "Categorical Topology"
	- Author of 32 scientific papers and 5 didactic publications
1996 - 2003:	Erasmus Coordinator Faculty of Sciences, University of L'Aquila
2004 - 2018:	Vice-rector for the International Relations and Projects, University of L'Aquila
2002 - 2010:	Consultant for European policies and Programmes, Region Abruzzo
2019 - today	Rector's Consultant for the Internationalisation Policies and Rankings

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

Nikolas Schöne[1*], François de Rochette[1], Boris Heinz[1,2]
*Corresponding author

1 Department of Energy Systems, Technische Universität Berlin, Einsteinufer 25, 10587 Berlin
e-mail: n.schoene@tu-berlin.de
T: +49-(0)30-314-28634
e-mail: b.heinz@tu-berlin.de
2 Hudara gGmbH, Rollbergstr. 26, 12053 Berlin
e-mail: bheinz@hudara.org

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.

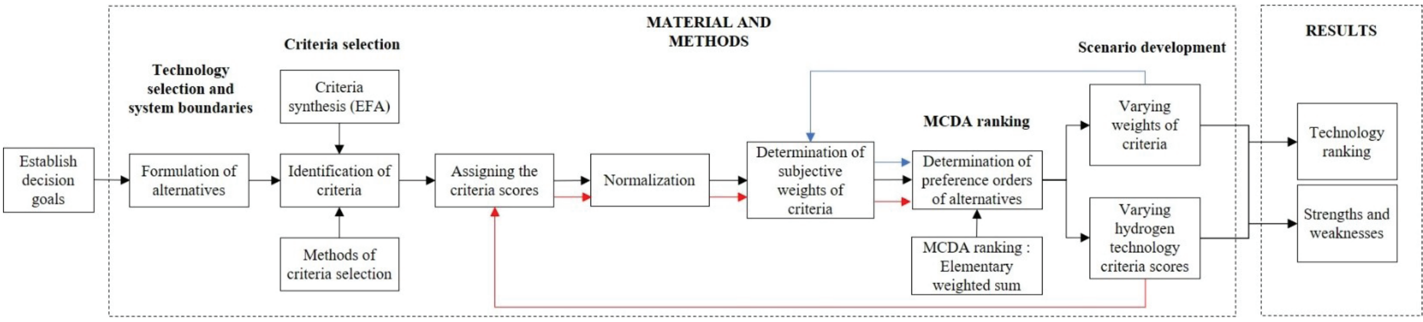

Fig. 1. Simplified and adjusted MCDA process in sustainable decision making [35-37].

- 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].

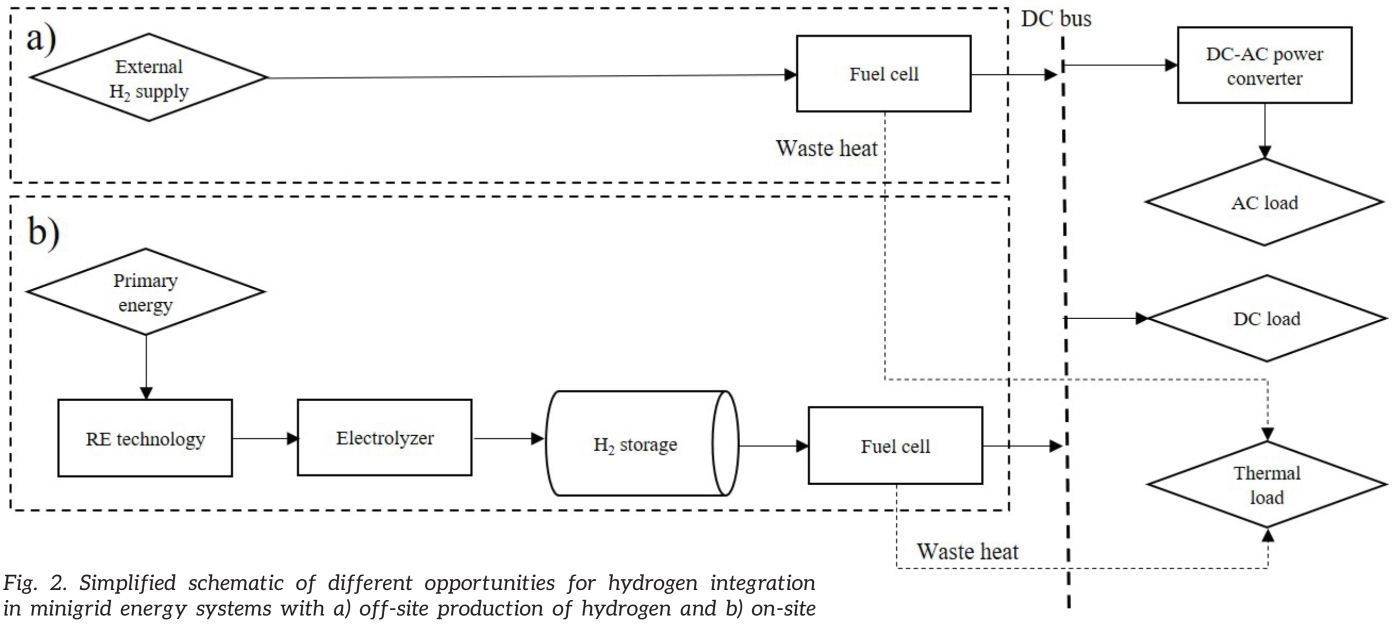

Fig. 2. Simplified schematic of different opportunities for hydrogen integration in minigrid energy systems with a) off-site production of hydrogen and b) on-site production and utilization of hydrogen.

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,

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

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 $\boldsymbol{\eta_i}$,

$$c_{v,i} = \frac{\sigma_i}{\eta_i} \tag{02}$$

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:

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

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 $\boldsymbol{C}$ into an importance order: $\boldsymbol{C_1 > C_2 > \ldots > C_n}$

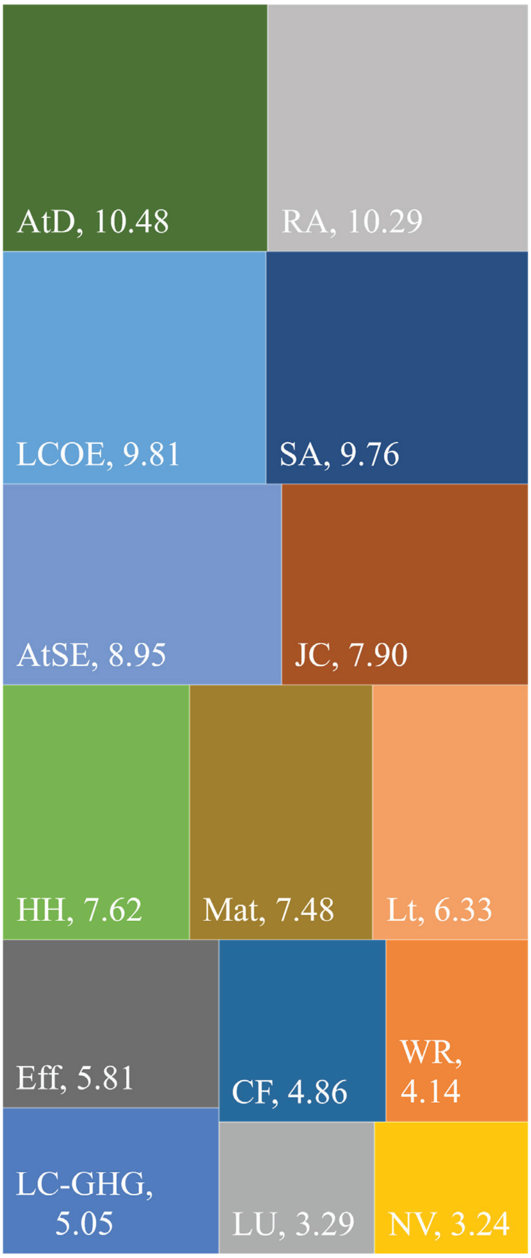

Fig. 3. Average ranking of the criteria obtained from the expert survey. LCOE = Levelized costs of electricity, HHE = Human health effect, SA = Social acceptance, JC = Job creation potential, Eff = Electrical efficiency, Mat = Maturity, DF = Capacity factor, RtD = Ability to respond to demand, AtSE = 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 $\boldsymbol{x_{wa}}$ with the weights $\boldsymbol{w_i}$ applied to criteria values $\boldsymbol{x_i}$ 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.

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.

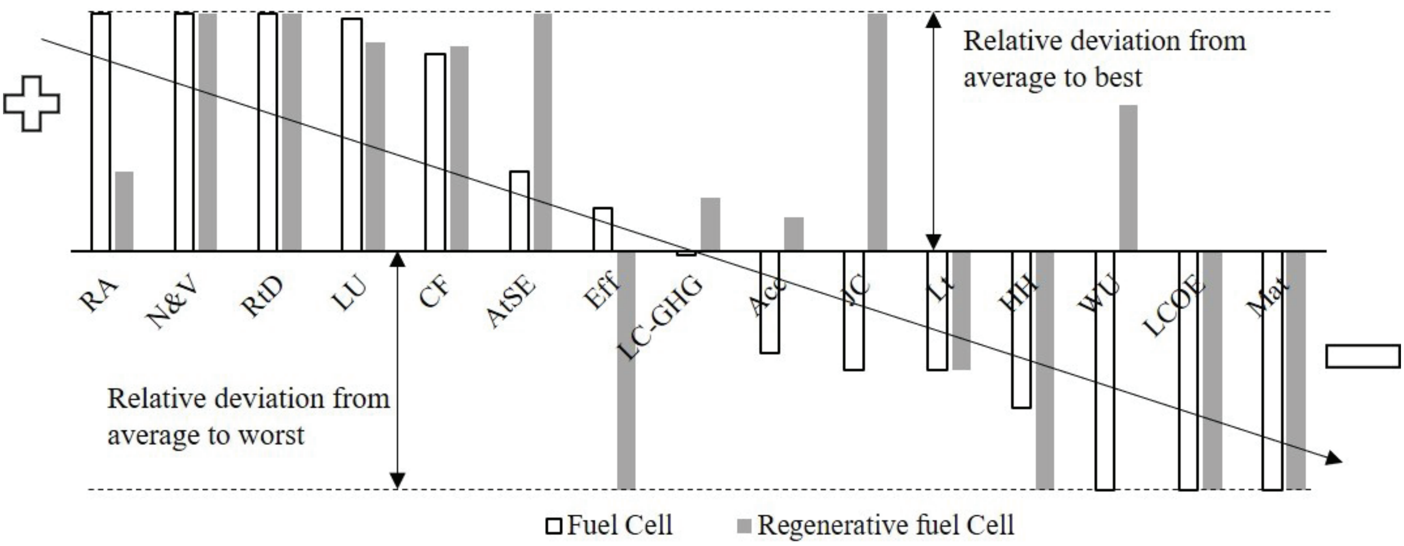

Fig. 4 Relative performance of the fuel cell and regenerative fuel cell in respective criteria.
LCOE = Levelized costs of electricity, HHE = Human health effect, SA = Social acceptance, JC = Job creation potential, Eff = Electrical efficiency, Mat = Maturity, DF = Capacity factor, RtD = Ability to respond 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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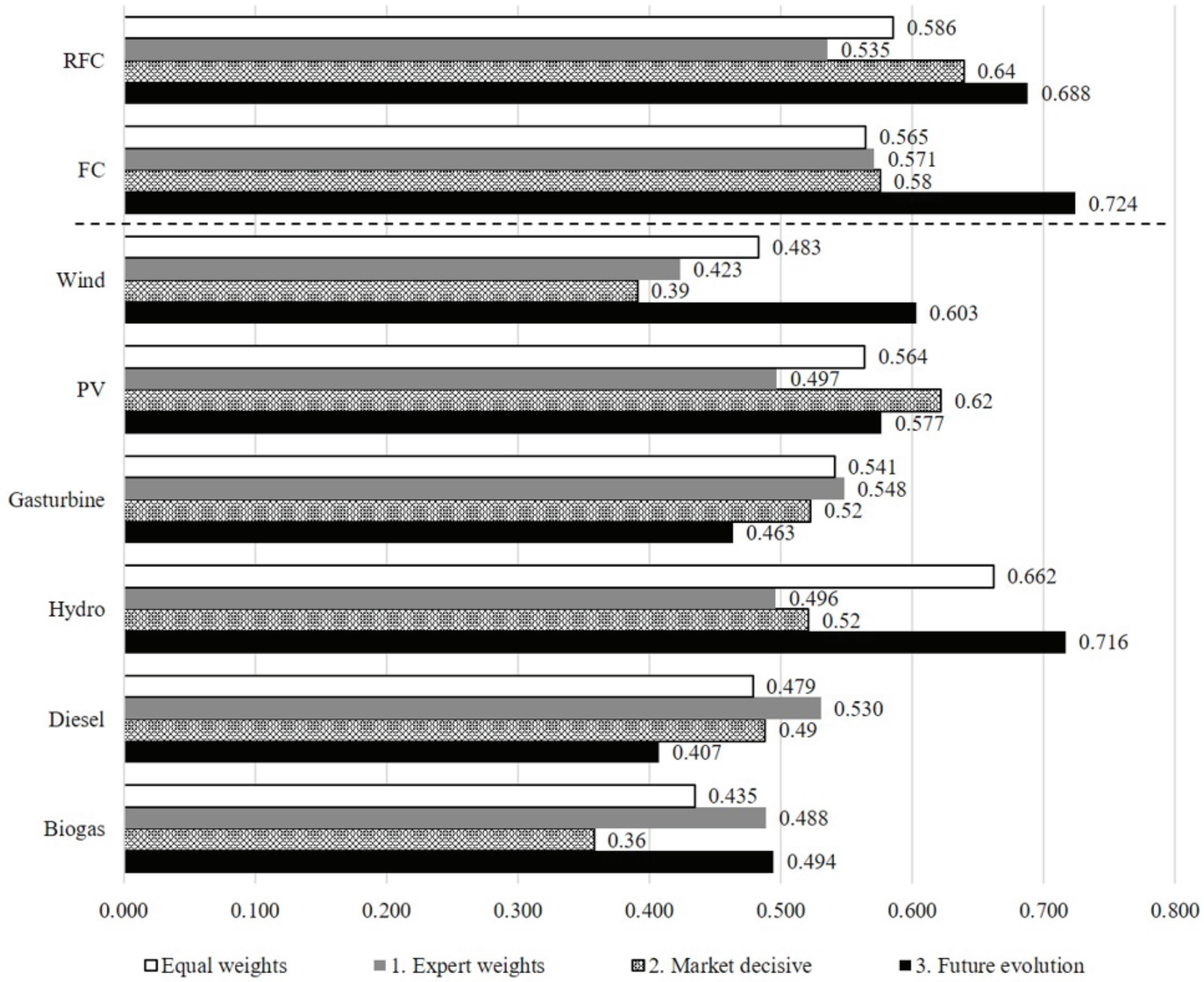

Fig. 5 Sustainability ranking of the power generation technologies for applying equal weights and applying the predefined scenarios.

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%

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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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Natural Gas Fermentation: A Promising Approach for Sustainably Meeting the World's Growing Nutritional Demands

Adel M. Al Taweel
Department of Process Engineering and Applied Sciences, Dalhousie University, Halifax NS, CANADA

e-mail: al.taweel@dal.ca

ABSTRACT

The rapid increase in world population, combined with the rising expectation for more nutritional diets in many rapidly developing economies, is creating a strong demand for the protein-rich materials used for human consumption and/or animal feed. Meeting such a demand is already exerting significant pressure on the environment and creating significant pressure for identifying and implementing more sustainable approaches for protein production and utilization. This looming problem needs to be addressed quickly, considering the recent accelerating rise in feed and food prices and their subsequent impact on the sociopolitical stability of several developing societies. This paper quickly reviews the environmental impact of current practices used for meeting the world's protein needs. It then introduces an environmentally-friendly novel approach for converting natural gas into Single Cell Protein that can be used as an ingredient in animal feed formulations. After reviewing the historical background for this approach and the various factors affecting its sustainability, the main impediments to its widespread adoption are discussed, and several means for enhancing the overall sustainability of the approach are presented.

Index terms: *Demand for nutritious food; Enhancing sustainability potential; Environmental impact; Single Cell Protein;*

I. INTRODUCTION

Over the past century, the food production pattern across the world has undergone a radical change as a result of adopting large-scale, intensive agricultural production practices. The increased efficiency of such systems led to reducing the prices for many daily necessities and helped to reliably nourish a rapidly growing population. For example, with an increase of just 10% in the agricultural land area used, the global food production doubled [1]. This, in turn, led to a significant increase in the global consumption of various sources of animal-based protein (e.g. Fish, Poultry, lamb/goat, beef), which is driven by the increase in the world's population, as well as the rising nutritional expectations throughout the world (Figure1). However, as shown in Figure 2, there is a very large disparity in meat production/consumption patterns throughout the world, where meat supply has grown in most of the world's regions [2]. However, the very efficient and cost-effective modern transportation system played a significant role in balancing the rapidly changing demand/production balance throughout the world.

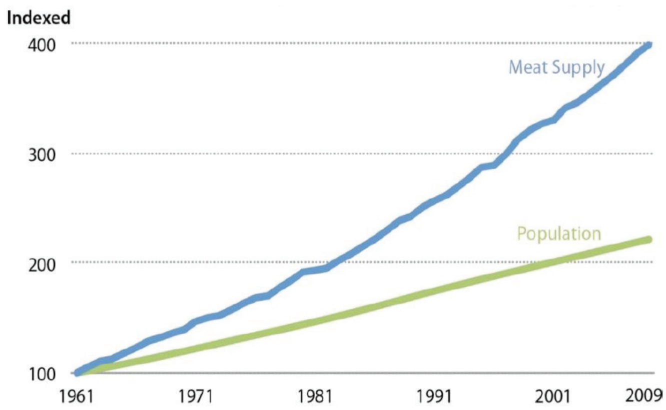

Fig. 1. Growth of the world's population and meet supply, Indexed 1961 = 100 [2].

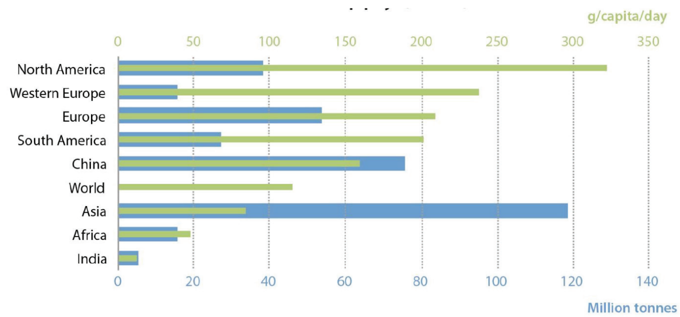

Fig. 2. Regional disparity in the total and per capita meat supply and consumption [2].

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As can be seen from Figure 3, there is a strong link between the per capita meat consumption and the level of income in many countries of the world, with the effect of increased income on diets being most pronounced among lower- and middle-income populations.

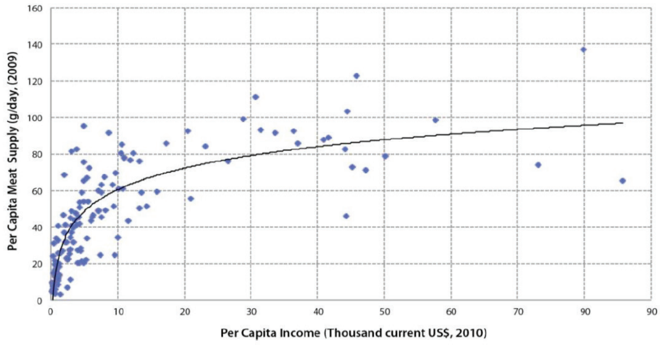

Fig. 3. Relationship between the level of income and the per capita meat consumption [2].

Finally, not only has the per capita meat consumption grown throughout the world but there are also, presently, many more consumers of meat and meat products. For example, the global human population grew from around 5 billion in 1987 to about 7 billion in 2011 and is expected to reach 10 billion people in 2050.

II. ENVIRONMENTAL IMPACT OF PROVIDING NUTRITIOUS FOOD TO THE WORLD

The rapid increase in the world's population, combined with the growing demand for improved nutrition in many developing countries, resulted in the projected global food demand to double by 2050. Unfortunately, a significant portion of the feed, food grains and oilseeds are being diverted into biofuels, resulting in critical pressures on suppliers worldwide. The recent rise in feed and food prices is but an example of the increased competing demands.

It exemplifies the need to consider unconventional sustainable approaches for food production that allow people to have physical, social, and economic access to sufficient and nutritious food that meets their dietary needs for a healthy and active life.

The deficiency is even greater in the case of protein, an essential nutrient in human health. Therefore, meeting such a demand is projected to exert significant pressures on the environment unless unconventional sustainable approaches for protein production are identified and developed. For example, the greenhouse gas, GHG, emissions from global livestock are estimated to already be larger than those emanating from all forms of transport (7.1 Gigatonnes of CO_2-equivalent per year, representing 14.5 percent of all anthropogenic GHG emissions), with cattle being responsible for about 65% of the emissions [2-8].

Furthermore, several studies estimated that 70-80 % of the water footprint caused by human activities is associated with agricultural activities. Future trends are even more worrisome. For example, whereas the global GHG emissions associated with agricultural activities grew by 8% in the period between 1990 and 2010, they are expected to grow further by 15% above 2010 levels by 2030. Furthermore, it is anticipated that the rise in agriculturally related GHG emissions will be particularly acute across Asia and sub-Saharan Africa since these two areas will account for around two-thirds of the increase in food demand over the first half of the 21st century. In addition, there are growing public health implications associated with livestock production and the magnitude of problems arising from the emergence of novel diseases at the animal-human-ecosystems interface.

One of the major causes of the aforementioned environmental impacts associated with Intensified Farm Animal Production (IFAP) is the large energy and resource inputs required for this type of production (including feed production and transport) and the enormous amounts of animal waste that is being produced in a very small area. For example, the USDA Agricultural Research Services estimated that the manure output from farm animals in the United States to be nearly 1 million tons of dry matter per day, of which 86% was estimated to be produced by animals held in confinement.
This heavy impact emanates from the following factors [5], where the impact of the various animal species is strongly influenced by the efficiency by which they can convert the nutrients present in the animal feed to meat:

- Methane from enteric fermentation,
- Nitrous oxide (N_2O) from excreted nitrogen, as well as from the synthetic nitrogenous fertilizers used to produce the animal feed.
- Misuse of water resources,
- Accelerated biodiversity loss
- Uncontrolled discharge of fertilizers and pesticides
- Deforestation resulting from the need for additional arable land to produce animal feed.

A significant reduction in the environmental impacts associated with meat consumption may be achieved by reducing the amount of wastage in the food supply chain and using more resource-efficient avenues for producing the proteins needed for human and animal growth [6, 9]. The latter approach is usually quantified using the feed conversion ratio, FCR, which is a measure of the efficiency with which the bodies of livestock convert animal feed into the desired output.

For animals raised for meat (such as beef cows, pigs, chickens, and fish), the output is the flesh or the body mass gained by the animal, represented either in the final mass of the animal or the mass of the dressed output. FCR is thus the mass of the input divided by the output (thus mass of feed per mass of meat) and can differ significantly between different animals and species:

- Compared with other livestock, ruminants have relatively poor FCR values. For beef cattle, in the USA, an FCR calculated on live weight gain can vary between 4.5–7.5, with the normal typical FCR value being above 6.
- On the other hand, commercial pigs had FCR values that vary between 3.5 and 4.1 depending mainly on their weight at slaughter.
- For sheep, the FCR values vary between 5 and 6 depending mainly on their age and the quality of the feed used.
- From the early 1960s to 2011 in the US, broiler growth rates doubled, and their FCRs halved, mostly due to improvements in genetics and rapid dissemination of the improved chickens. Consequently, the global average FCR is around 2.0 based on live weight and 2.8 based on the slaughtered meat weight.
- The best FCR are encountered in aquaculture, where Atlantic salmon and catfish had an FCR of around 1, while tilapia is about 1.5.

The factors mentioned above constitute severe challenges to achieving food and nutrition security and led to the emphasis being placed on developing new food production systems that incorporate "improved public health and welfare" as one of the main factors taken into consideration. The concept of "Sustainable Diet" advocates adopting a diet with a reduced environmental impact that can simultaneously contribute to the elimination of poverty, food and nutrition insecurity, and poor health outcomes [10]. This concept is very similar to the "Climate-Smart Agriculture" concept advocated by FAO in which the system fights climate changes while simultaneously enhancing food security, as both are closely related [11].

Several investigators and agencies have proposed the implementation of positive and negative carbon taxes to achieve those goals. In this approach, the emission intensities of different meat products are taken into consideration when applying a carbon tax [12]. However, such measures need to be cautiously evaluated before implementation to unnecessarily disturb the demand/supply balance for such a critical commodity.

Since the feed costs presently constitute the major production cost factors for all livestock operations, market forces have already played a significant role in promoting the marketing, and consumption, of livestock that can efficiently convert animal feed into animal meat (e.g. poultry and fish). This is highlighted by the staggering growth in demand for poultry in South East Asia (in excess of a 7-fold increase between 2000 and 2030), which is primarily attributed to increasing per capita consumption rates rather than increasing population levels [13] as well as in the strong rise demand for fish products discussed below.

Similarly, seafood consumption is generally increasing in many parts of the world and is widely promoted as part of a healthy diet. Fish meat has a higher protein content compared to terrestrial animal meat, and fish have a lower feed conversion rate FCR than land animals. More protein can thus be produced by growing fish at lower feed rates. Furthermore, fish protein is highly digestible and rich in essential amino acids (including methionine and lysine), which are limited in animal-sourced protein.

However, food safety risks such as heavy metal content could be of concern, particularly with contaminated, wild fish. Negative social outcomes are also associated with aquaculture in countries where there are weak regulatory frameworks, and there is concern about the possibility of emerging diseases and disease transmission due to increased intensification and globalization.

III. AQUACULTURE CONTRIBUTION TOWARDS MEETING THE WORLD'S PROTEIN DEMAND: ENVIRONMENTAL IMPACT

As shown above, the global demand for high-quality protein-rich foods will continue to increase as the global population grows and as the nutritional demands in the rapidly developing countries accelerate. This is clearly shown in Figure 4, where the capture fisheries reached a peak around 1988, whereas, with its very good feed conversion factors, aquaculture has grown exponentially over the past three decades to fulfill some of the demand.

It is presently the fastest-growing animal protein industry. However, despite the increased output from global aquaculture, farming of marine fishes is unlikely to overtake marine capture production in the near future [14]. Furthermore, the contribution of non-fed aquaculture declined from 44% in 2000 to about 30% percent in 2018. That trend is expected to be accelerated by the development of low-cost, environmentally-friendly feed.

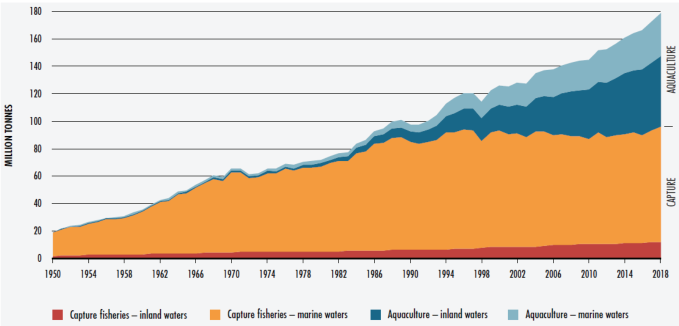

Fig. 4. World capture fisheries and aquaculture production [14]

The World Bank recently undertook an excellent study of aquaculture's present and future role in collaboration with the Food and Agriculture Organization of the United Nations, FAO, and the International Food Policy Research Institute [15]. It estimates that by 2030, aquaculture will provide close to two-thirds of the global food fish consumption at the same time when catches from wild capture fisheries level off, and demand from an emerging global middle class substantially increases.

The fastest supply growth is likely to come from tilapia, carp, and catfish. Furthermore, fish is playing an increasingly important role in economic development and world trade, So, for example, in 2014, 38% of all fish produced in the world was exported, and in value terms, over two-thirds of fishery exports by developing countries are directed to developed countries. Fisheries and aquaculture are a vital source of jobs, nutritious food and economic opportunities, especially for small-scale fishing communities. However, threats from large-scale disease outbreaks in aquaculture and climate change-related impacts could dramatically alter this.

Global fish production is estimated to have reached about 180 million tonnes in 2018 (Figure 5),

with a total value in excess of US$ 400 billion, of which 82 million tonnes (with the aquaculture production valued at about US$ 250 billion). Of the overall global consumption in 2018, 156 million tonnes were used for human consumption (equivalent to an estimated annual supply of 20.5 kg per capita), while the remaining 22 million tonnes were destined for non-food uses, mainly to produce fishmeal and fish oil (Figure 5). Total fish production has increased in all continents over the last few decades but has almost doubled during the last 20 years in Africa and Asia [14].

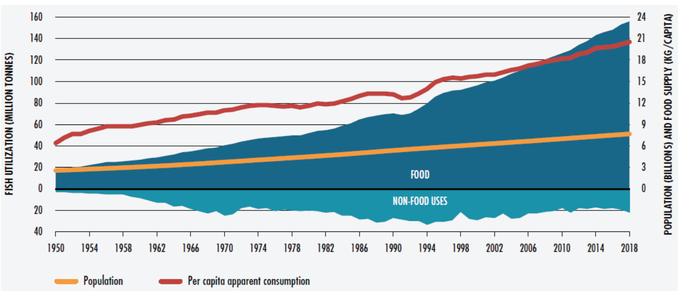

Fig. 5. World Fish utilization and consumption patterns [14].

One of the main reasons behind the growing role that aquaculture plays in meeting the growing demand for food security can be attributed to the rapidly deteriorating environmental conditions and overfished stocks. Based on FAO's assessment, the fraction of fish stocks that are within biologically sustainable levels decreased from 90% in 1974 down to 66% in 2017; whereas the percentage of stocks fished at biologically- unsustainable levels increased from 10% to 34% percent in the period (Figure 6).

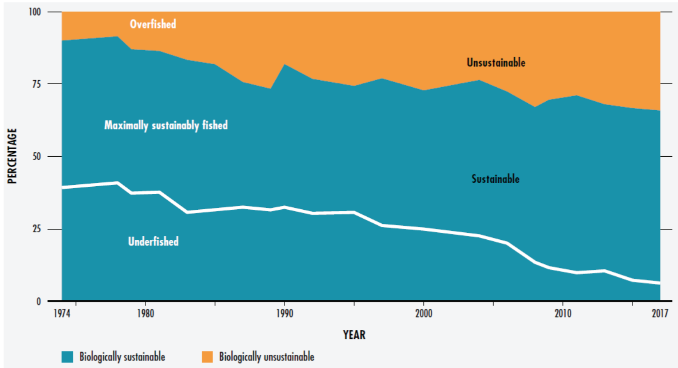

Fig. 6. Global Trends in the State of the World's Marine Fish Stocks, 1974- 2017 [14].

Following a decade-old trend, aquaculture is expected to continue to be the driving force behind the growth in global fish production, with a projected production capacity of 109 million tonnes in 2030 [14]. Consequently, the share of farmed species in global fishery production (for food and non-food uses) is projected to grow from 46% in 2018 to 53% in 2030 (Figure 7). However, somewhat slower growth rates are predicted in the decades afterwards due to the increased total production capacity, the broader adoption and enforcement of environmental regulations, and the reduced availability of water and suitable production locations. Aquaculture production is also expected to continue the transition from extensive to intensive operations, aiming to better integrate production with the environment by adopting ecologically sound technological innovations.

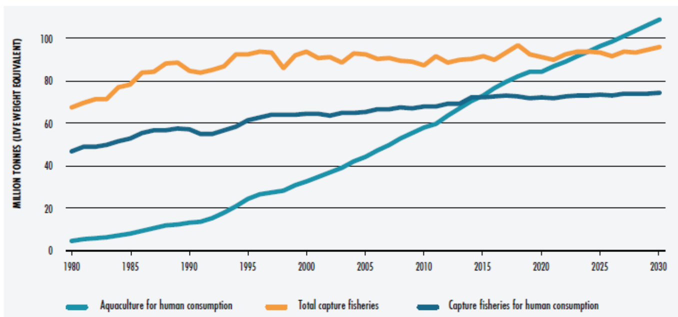

Fig. 7. Global fish production from capture fisheries and aquaculture operations [14].

1. However, the sustainable development and growth of the aquaculture industry is heavily dependent on the availability of inexpensive

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sources of protein since feed accounts for 60-80 % of the operational cost in intensive aquaculture and 40-60 % in semi-intensive aquaculture systems [4]. Although several protein sources can be used in preparing aquafeeds, fishmeal and fish oil are considered essential for maintaining a rapidly-growing and healthy fish population unless suitable, or better alternatives, can be used. While soy is presently the most common terrestrial plant protein used as fishmeal substitute, many environmental concerns surround the land-use, and fertilizer run-off, requirements associated with soy production. Additionally, palatability and anti-nutritional factors, as well as unintended biological consequences, limit the broad application of unmodified soy and other plant proteins. To mitigate this problem, the industry prioritizes means for improving feed conversion ratios, increasing the recycling of aquaculture fish processing waste, and finding alternative protein sources that can reduce the strong dependence on fishmeal/fish oil [16].

2. The main factors contributing to the growth of the global fishmeal market are increasing demand for naturally derived protein additives in animal feed, expansion of the feed industry, extensive development of salmon aquaculture, and increased consumption of fish as a significant food in various regions of the world. Unfortunately, the over-fishing of the oceans and the severe degradation of the oceanic environment resulted in decreasing fishmeal supply until around 2016 (Figure 8). The recent increase in fishmeal availability can be attributed to increasing world price and enhanced raw material availability obtained from whole fish and fish-residue, a by-product of processing. As shown in Figure 9, a growing share of fishmeal and fish oil will be obtained from fish residue.

3. Aquaculture has long been criticized for “using fish protein to make fish protein”. However, implementation of EU regulations (Commission Delegated Regulation No. 1394/2014) is expected to enhance the availability of fishmeal feedstock. This regulation aims to gradually eliminate the practice of discarding undersized fish, under-utilized species, at sea and opens up the possibility for processors to convert this by-catch or marine “rest raw material” into value-added ingredients due to the high protein and oil content of this by-catch.

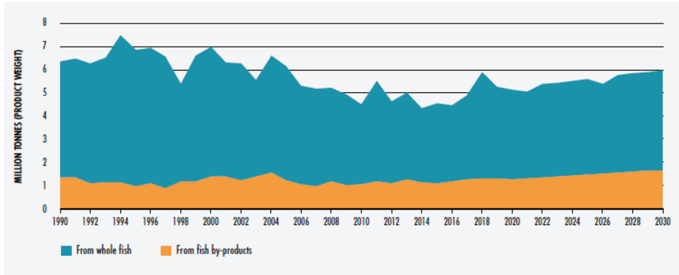

Fig. 8. World fishmeal production, 1990-2030 [14]

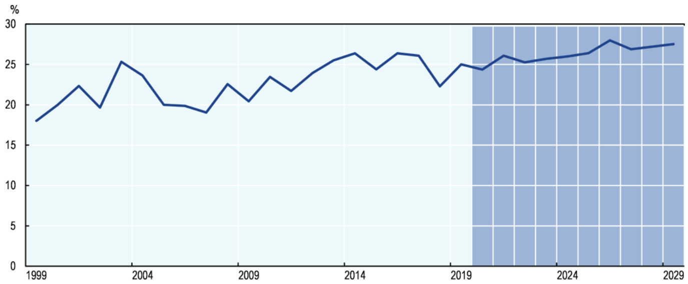

Fig. 9. Share of total fishmeal production produced from the fish residue [17].

The rapid degradation of fishmeal quality and availability resulted in a multi-fold increase in prices (Figure 10), and the fishmeal prices are expected to increase at even a higher rate than that of most fish species (Figure 11). The potential formation of fishmeal shortages (Figure 12), will exasperate that trend unless viable alternatives are identified to meet the world’s nutritional demands cost-effectively without damaging the environment [4, 5]. The emphasis on significantly reducing the footprint of the latter stipulation is driven by the conclusion of many comprehensive environmental impact studies that covered a span of more than 15 years [19-22].
The many life cycle analyses were undertaken that clearly identified that the global environmental performance of aquaculture production is dominated by:

- Aquafeed production is a key driver for climate change, acidification, and cumulative energy use, with the fish-, and livestock-derived ingredients accounting for the highest proportional environmental costs of production. It is also strongly affected by the feed use efficiency.
- Sea-based systems outperform land-based technology in terms of energy demand.
- Sea-based systems have a generally higher FCR than land-based ones.
- The fish farm stage of production is a significant contributor to only one of the quantified impacts, namely, eutrophying emissions. Different aquaculture systems and technology components may exert considerably different environmental impacts but, on the average, open systems generate more eutrophying emissions than closed designs.
- The environmental impacts of aquaculture

production are highly variable between regions, indicating substantial scope for environmental performance improvement in the industry as a whole.

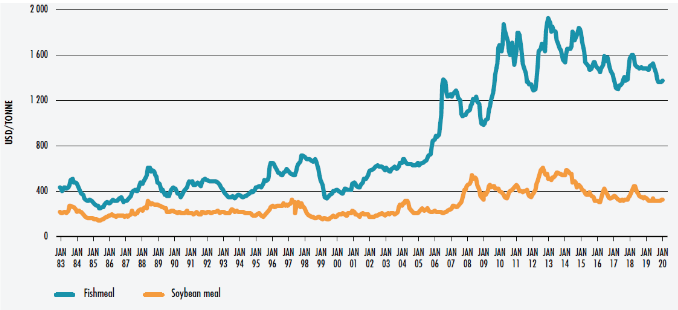

Fig. 10. Fish and Soyameal price trends (prices CIF Rotterdam and Hamburg) [14]

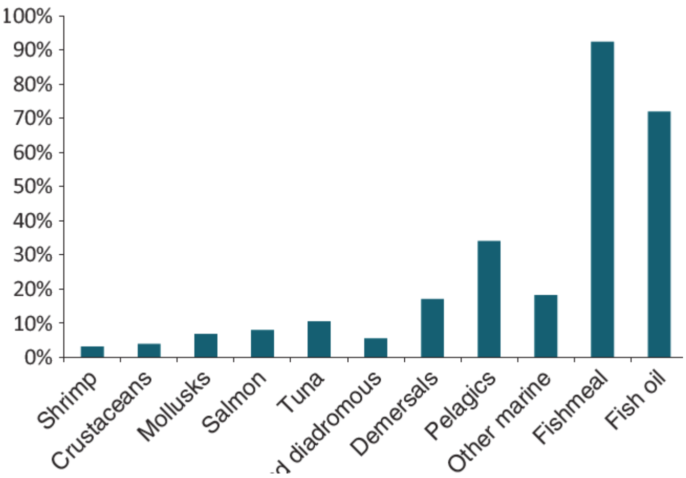

Fig. 11. Projected change in aquaculture commodity prices (between 2010 and 2030) [15].

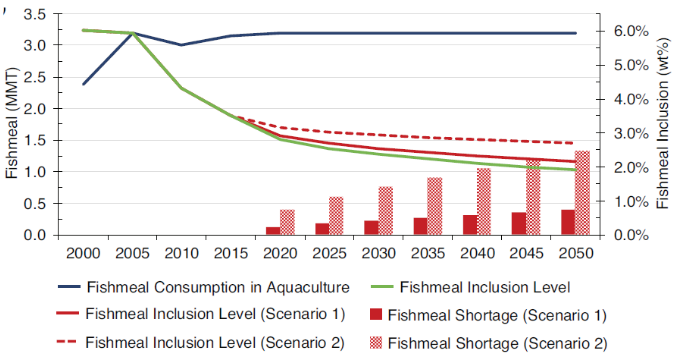

Fig. 12. Projected Fishmeal consumption in aquaculture applications (2015-2050). An average feed conversion ratio, FCR, of 1.2 was used [18]

IV. EFFORTS AIMING AT THE DEVELOPMENT OF ENVIRONMENTALLY-FRIENDLY AQUAFEED

A significant reduction in the environmental impact associated with meat consumption may be achieved by reducing the amount of wastage in the food supply chain and using more resource-efficient avenues for producing the proteins needed for human and animal growth [6, 9]. The magnitude of the problem can be easily grasped by realizing that in 2018, the global animal feed production is ca 1.1 Billion tonnes worth over $ 400 billion. To properly address a problem of such magnitude, well-planned collaborative, transnational efforts between private and public sectors are needed if one has to solve such a major problem. Some initiatives have already started, and one hopes that such actions will accelerate if a sustainable solution to the problem of climate change is to be implemented.

For example, to promote this trend and help develop innovative approaches, the European Institute of Innovation and Technology, EIT, supported the establishment of “Climate-KIC International Foundation”.
This foundation is Europe’s largest public-private innovation partnership whose mission is to catalyze systemic change through innovation in the areas of human activity that have a critical impact on greenhouse gas emissions (cities, land use, materials and finance). It also aims at creating climate-resilient communities.

It, in turn, created “Project-X” the mission of which is “to radically transform the sustainability performance of 10 industry value chains most responsible for biodiversity decline and climate change impacts, over the next ten years. They accomplish this by accelerating access to finance, markets and innovation at the system level and can mobilize up to $10b of additional investment into adopting sustainable innovations globally. They also can help in securing a market commitment from top leaders in the industry.

One of the sub-projects promoted by the aforementioned organization is “Feed-X”; a program the central idea of which is shifting 10% of the global feed industry (about 107 M tpa) towards more sustainable production of animal feed. This objective is to be accomplished using novel, alternative solutions undertaken by independent entrepreneurs.

The criteria used in selecting such approaches are based on several factors, including:

- reducing harmful environmental effects caused by deforestation,
- reducing the carbon footprints, and
- reducing irresponsible fishing practices.

Several large private and public organizations (such as: Skretting, IKEA, World Wildlife Fund, Climate-KIC, and other mission-aligned partners) have already subscribed towards such activities. Armed with the financial and technical support brought in by so many partners,

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V. CONVERTING HYDROCARBONS INTO SINGLE CELL PROTEIN

A. A Historical Perspective

The term single cell protein, SCP, refers to sources of protein extracted from pure or mixed cultures of algae, yeasts, fungi or bacteria, a practice that has been used for millennia by many societies to enhance the nutritional value of certain foods. However, the large-scale use of SCP as a nutritional supplement has its historical roots in Germany, where, during the First World War, about half of all the imported protein was offset by yeast [24, 25]. Some of that tradition is still alive where, for example, single-cell proteins are consumed daily by millions of people and form the basis of popular brands such as "Quorn, Marmite and Vegemite".

Unfortunately, the carbohydrates that have been traditionally used as a substrate for such operations are presently not easily available and/or cost-effective. On the other hand, spent yeast cells from ethanol fermentation processes are commonly blended with dried distiller's grains, and "solubles" in terrestrial animal feeds. However, the high fiber content of this blend limits its use in aquaculture [26]. Similarly, algae are grown commercially in ponds or bioreactors for use in food, cosmetics, oil and nutritional supplements. However, the large-scale application of algae as an alternative protein source is presently limited by technical challenges and high production costs. Consequently, significant efforts were dedicated over the past several decades aiming towards the use of hydrocarbon-based substrates for the production of SCP.

The growing interest in using biotechnology to address the need for meeting human protein consumption resulted in an explosive growth in R&D, patenting and commercialization. These are reviewed by Ritala et al. [27], who provided excellent insight into the technical and commercialization factors. The authors also noted that industries and universities in China have been very active in filing patents related to SCP in recent years, particularly those related to SCP production by fermenting agricultural or food residues with bacteria, yeast and mixed populations. Consequently, more than half of the patents awarded since 2001 having been filed in China.

The attempt to develop large-scale operations for the production of SCP began in earnest in the 1960s when British Petroleum became interested in the growth of microorganisms in the wax fraction, which has to be removed from gas oils. A 16,000 tpa plant was built with the product being marketed as a replacement for fish meal in high-protein feeds and as a replacement for skimmed milk powder in milk substitutes [23]. The Soviets were particularly enthusiastic about this approach and established several large "protein-vitamin concentrate plants" next to several refineries. However, the problems associated with the complete removal of heavy hydrocarbons from the bacterial biomass, combined with the rapid increase in the value of all liquid petroleum fractions, resulted in the adoption of other less expensive hydrocarbon-based substrates such as methanol.

For example, ICI commissioned a 60,000 tpa plant based on the use of methanol as a substrate, in which a bacterium (Methylophilus methylotrophus) was grown using what is still considered to be the world's largest airlift fermenters (1,500 m3 each). The product was marketed as a feed constituent providing a source of energy, vitamins and minerals, as well as a highly balanced protein source.

Following ICI success, Shell Research Center in Sittingbourne developed a continuous process for directly converting methane into SCP. This approach avoids the toxicity problems associated with the use of alkanes and has significant economic advantages over other hydrocarbon-based SCP routes. The economic advantages of using methane as compared to other substrates are quite significant. It is a relatively inexpensive substrate that is available in a highly pure state worldwide, and its use allows for achieving higher reaction rates, better selectivity, and greater conversion efficiencies, factors that are critical for the sustainability of this approach. Shell's technical achievements are summarized by Hamer [28].

The company planned for the establishment of a 100,000 tpa plant in Amsterdam. However, all commercialization activities by both ICI and Shell were stopped because of the turmoil that plagued oil and gas prices at that time, and by concerns about the ability to compete with abundant supplies of relatively low-priced soymeal and fishmeal. It is, however, interesting to note that the airlift reactors built by ICI were used by "Marlow Foods UK" to produce one of the most successful SCP products exclusively used for human consumption as a meat substitute "Quorn™" [29].

At present, three major organizations/consortia have a commercial interest in converting natural gas into SCP. Unibio A/S leads the first group, the second by Calysta Inc., whereas VTT Ltd. is investigating various options for coupling farm methane generation with the production of microbial oil and feed protein [30]. An India-based startup, "StringBio" recently got involved in the field [31].

In the mid-1980's, Dansk BioProtein A/S was established to commercialize the conversion of Methane into SCP using the naturally occurring Methane-consuming microorganism (Methylococcus capsulatus) discovered by Dr. M. Naguib from the Max Planck Institute. In collaboration with the Danish Technical University, DTU, the company improved the design of their fermentor, cumulating with the award of the patents protecting the use of the U-Loop bioreactor. The company then collaborated with a Norwegian consortium that included Statoil, but that relationship did not survive long because of disagreement of future R&D plans [32].

Efforts aiming at developing the technology continued in Denmark, where Unibio A/S was founded in 2001. It collaborated extensively with the DTU, and in 2010, a 7.5 m3 pilot facility was built at the University of Trinidad and Tobago. In 2016, Unibio A/S inaugurated an 80 tpa pilot facility built in Kalundborg (one of the world's leading centers for demonstrating the circular economy concept and the advantages of process integration [33, 34]).

Samples from that plant were used for additional feed tests that revealed that its trademarked product, Uniprotein®, can be used as a partial replacement of prime fishmeal without adverse effects and has gained approval from the European Union for inclusion in feed prepared for all animal and fish species. Furthermore, its use may enable for eliminating the need for incorporating medical zinc oxide in piglet feed, a practice that may be in the process of being banned in Europe. In partnership with the Russian firm Protelux, the first full-scale production plant (6,250 tpa) was completed in 2020, in which four 35 m high U-Loop fermenters are used (Figure 13). The protein-rich product is intended as an ingredient to produce feed for the pig and feed markets. The low cost of natural gas and electricity is expected to create competitive advantages for Russia when it comes to the production of bio protein [35].

Fig. 13. Unibio/P plant in Russia [35].

The other group that is very active in this field owes its existence to the period near the end of the 20th century, where interest in converting methane into SCP was re-stimulated by the availability of abundant supplies of North Sea natural gas, the steady increase in the price of fishmeal, and the presence of large local Salmon aquaculture operations. Following the failure of the joint venture with "Dansk BioProtein A/S", Norferm AS was developed as a joint venture between Statoil and DuPont. This consortium designed and built a 10,000 tpa plant at Tjeldbergodden, Norway that started operating in 1999 [36]. Their product trademarked as "BioProtein" was widely marketed and approved for use as a safe constituent in animal feed formulations and limited human consumption [37].

However, the plant was shut down in 2006, presumably due to the high NG prices charged at that particular time and location. The IP was consequently transferred to "BioProtein" (a consortium of three Norwegian academic institutions), which continued to do work validating the positive health effects of microbial protein in salmon, pigs and other livestock [32].

A decade later, Calysta (a company founded in Menlo Park, California in 2011) acquired the technology from BioProtein A/S in 2014, thereby merging their expertise in fermentation biology with a proven-track commercial-scale fermenter design and an EU-approved microbial protein. In collaboration with the Centre for Process Innovation and Otto Simon Ltd, a 100 tpa technology development and market introduction facility was designed and built-in Teesside, UK [38]. Their product is marketed as "FeedKind®" protein. Efforts are presently underway to obtain approval in the US for farm animals, pets, and ultimately human consumption.

Calysta announced a joint project with the multinational feed giant Cargill to establish a large-scale production facility in half of Cargill's site in Memphis, TN. This facility is to occupy 37 acres to produce 20,000 tpa of FeedKind® protein in the first phase, with an additional 180,000 at a later stage [39]. This plant will be home to the world's largest gas fermentation operation to produce Calysta's FeedKind® protein. In 2019, the venture arm of BP (the British oil and gas giant) announced its 30 $ Million investment in the partnership, with BP supplying power and gas to Calysta feed protein plants [40]. However, although the sod-turning event took place in April 2017, there is no publicly available news concerning the progress achieved in this project.

Recently, Calysta formed a joint venture with Adisseo in Paris (a world leader in feed additives for animal nutrition) and the Bluestar Group in Beijing to construct a FeedKind production facility in China. The last organization is one of China's largest

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chemical organizations that focuses on new chemical materials and animal nutrition and is connected with the US's Blackstone Group as a strategic investor. The production facility is located in the Changshou National Economic and Technological Development Zone (Chongqing City) and will initially produce 20,000 tpa of FeedKind protein, exclusively for Asian markets, with a second phase bringing in an additional capacity of 80,000 tpa. Construction of that facility started in the first week of 2021 and is projected to come online in 2022 [41]. Considering that China is the world's largest fishmeal importer, the construction of such a facility represents a big step towards improving the security of supply for high-protein content ingredients wildly used in preparing compounded feed formulations.

VI. TECHNICAL CHALLENGES FACING THE PRODUCTION OF SCP

A. Introduction

Although many microorganisms can be used to convert natural gas into high-protein biomass, attention is focused on Methylococus capsulatus (Bath) because its suitability for large-scale operations has already been proven, and an extensive database for its suitability as an ingredient in animal feed and human consumption already exists. It is a naturally occurring microorganism responsible for much of the methane naturally emitted by the soil being converted into nutritious compounds that are consumed by lower-level organisms. The overall reactions involved can be represented by [42]

$$CH_4 + 0.104NH_3 + 1.450_2 \rightarrow 0.52\, CH_{1.8}O_{0.5}N_{0.2} + 0.48\, CO_2 + 1.69\, H_2O$$

The spray-dried form of the bacteria is a light brownish, free-flowing granulate that resembles powdered milk but, as shown in Figure 14, has a substantially higher protein and fat contents with high amounts of phosphorus, potassium and magnesium. Furthermore, as shown in Table I, the amino acid profile of the protein obtained from that bacteria closely matches that of high-quality fishmeal and is thus well suited as direct feed for animals, particularly those with a short life span (e.g. shrimp, poultry, calves, ducks, fish, dogs, and cats).

The product produced by both companies performed well in the extensive sets of feeding tests undertaken by the companies and independent agencies. They confirmed that not only can it be used as a replacement for fishmeal, but its ability to stimulate the immune system, combined with the high digestibility of the nitrogen present in the protein, resulted in achieving enhanced growth rates, improved animal survival rates, better nitrogen retention, and reduced susceptibility to digestive tract inflammation [42-45]. Most importantly, significant improvement in the feed conversion ratio was observed as the fishmeal was replaced with the alternate bio protein, a factor that is critically relevant to the operational profitability [44]. It may therefore be considered as a "super-prime" fishmeal.

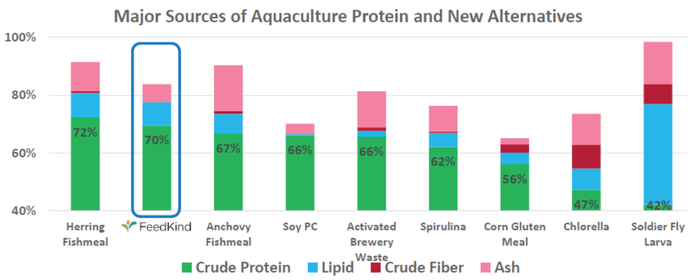

Fig. 14. Major sources of protein-containing feed ingredients [42]

Table I

PROFILE OF SELECTED ESSENTIAL AMINO ACIDS PRESENT IN PROTEIN SOURCES [46].

	Skim milk powder	Fish meal	Soya bean meal	BioProtein
Crude protein	36,1%	63,8%	45,8%	70,0%
Amino acids (g/kg):				
Methionine	8,4	16,1	5,6	18,7
Cystein	2,7	5,6	6,1	4,2
Lysine	26,0	44,0	24,6	43,0
Threonine	14,8	24,3	15,7	31,0
Tryptophan	4,7	6,6	5,5	14,8
Arginine	11,3	33,8	29,2	41,3
Total	69,9	130,4	86,7	153,0

*** With the exeption of BioProtein, the values listed above are from: The Amino Acid Composition of Feedstuffs, Degussa AG.**

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B. Production Methodology

The aforementioned natural gas fermentation approach used by the two leading technology providers in this field (Unibio A/S and Calysta) is relatively simple and relies on the use of processing steps that are commonly encountered in many food-processing operations (Figure 15). The two organizations use almost identical main microorganisms (Methylococus Capsulatus) and the same bioreactor type (continuous, forced circulation, loop bioreactor).

The major difference between both companies lies, therefore, in the design and configuration of their respective patented bioreactors [47, 48]. Unfortunately, only a few independent laboratory-scale experimental investigations were conducted to assess the effect of various design and operating conditions on the reactor performance of [49]. However, in order to enhance the bioreactor productivity, all the experimental and simulation findings point out to the need for enhancing the rate of interphase mass transfer, which is usually quantified by the kLa value. This is driven by the very low water solubility of the gases involved in this process CH4, O2.

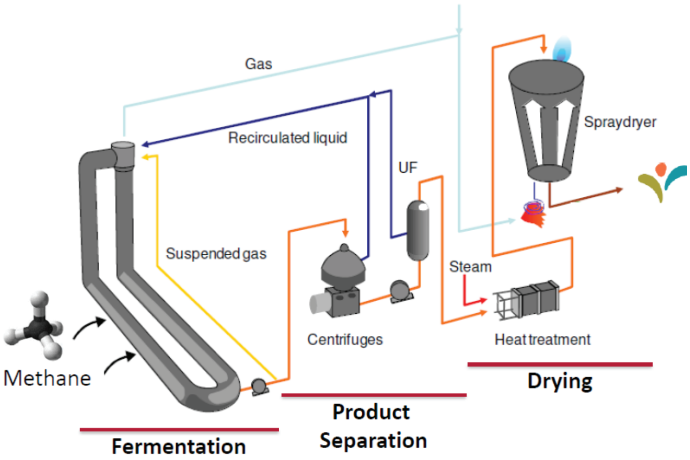

Fig. 15. Typical flow diagram for the bioconversion of natural gas into animal feed [42].

The bioprocess engineering approach used by both companies mimics what happens in nature but attempts to create an environment that maximizes the rate by which the microorganisms grow and the efficiency by which they utilize the substrate “Methane”. This, in turn, is affected by many parameters such as: type and concentration of microorganism used, broth composition, liquid phase concentration of methane/oxygen/CO2, operating temperature and pressure, pH, micronutrients, and mixing patterns in the bioreactor. In order to reduce the overall capital costs and avoid the complexities associated with the recycling of unutilized reactants, the bioreactor is operated in a fashion in which the gas phase passes only once through the reactor. In contrast, the liquid broth is recycled through the fermentor/separator using a pump. Consequently, it is necessary to achieve very high conversion efficiencies of the gaseous reactants (CH4 and O2) in order to lower the operating costs [50]. Three reactor types that can meet this requirement have been successfully used for converting natural gas into bioprotein at the lab scale [49].

All of these can be considered variants of the simple multiphase recirculating loop reactor system but differ in the method used for inducing fluid movement (e.g. pumps, in-line axial flow mixers, or airlift) and in the orientation of the tubular section (vertical vs. horizontal). In all cases, it is necessary to maintain:

- high interphase mass transfer rates,
- removing the heat generated by the exothermic biochemical reaction, and
- reducing the concentration of inert gases and CO2 in the recycle stream.

A significant part of the unit is also operated at somewhat elevated pressures (2-5 atm) in order to overcome the limitations caused by the low solubility of the reactant gases. Optimally designed reactor systems are therefore essential for achieving a sustainable biochemical operation. A simple analysis of the forced-loop bioreactor performance (that considers the impact of CO2 generation on interphase mass transfer) clearly identifies that the system's overall performance is mass transfer limited [51, 52]. It also suggests that reactor productivities as high as 12 kg/h m3 can be achieved provided that a relatively high mass transfer coefficient can be achieved without detrimentally affecting the microorganisms (Figure 16).
This productivity is almost 3-fold what previous systems achieved and suggests that substantial reductions in capital and operating costs can be achieved under optimal design and operating conditions.

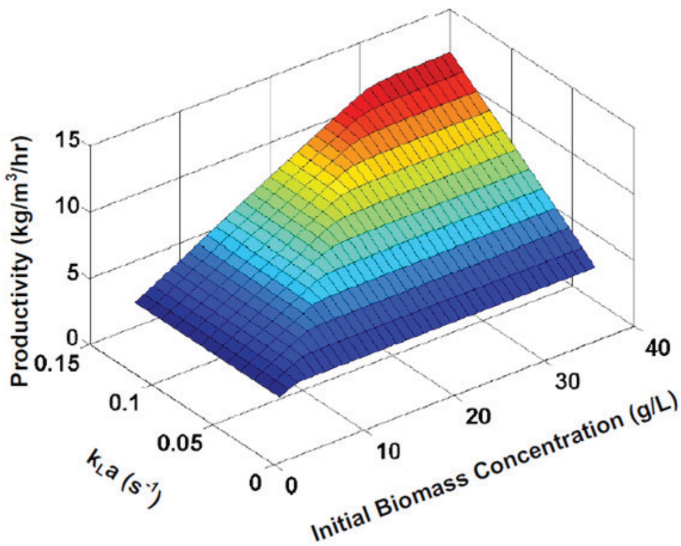

Fig. 16. Effect of operating conditions on the average bioreactor productivity (5 atm, 45°C, recycled CO2 is 10% of equilibrium value) [52].

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In this regard, it is interesting to note that the recent results (obtained using the slowly-coalescent system of 0.05 M KCl) indicates that very high volumetric mass transfer coefficients can be achieved by incorporating static mixers in the vertical legs of the U-Loop bioreactor used by Unibio A/S in their process [53]. These results are several times larger than the upper range shown in Figure 16, suggesting that there may be room for further enhancement provided that the microorganisms are not adversely affected by the high shear rates encountered [51].

VII. ECONOMIC AND ENVIRONMENTAL CHALLENGES FACING THIS APPROACH

A. Introduction

The proposed approach to producing high-protein biomass offers several environmental advantages when compared to the intensive livestock approach, where about a quarter of the Earth's land area is dedicated to grazing (mostly for cattle, sheep and goats), and a third of all arable land is used to grow feed crops for livestock. The bioprotein produced is a non-polluting non-GMO microorganism (free from toxins, dioxin and heavy metals due to the controlled production process and the use of food-grade trace minerals), the production of which poses very low water demands and land-use requirements.

The history of previous industrial attempts to convert natural gas into a protein-rich animal feed component clearly shows a strong vulnerability to fluctuations in the price of the main input constitutes (natural gas and energy, Figure 17), as well as the prices of alternate feed formulation constituents, such as Soymeal. A preliminary techno-economic study, in which a sensitivity analysis to various factors affecting economic viability was undertaken, confirmed this vulnerability to market forces [54].

It also indicated that the economic sustainability of this approach is mostly influenced by the price commanded by the products, and to a lesser extent, by the cost of the feedstock used. These observations are mostly driven by the relatively large capital costs involved in such operations (the second most important parameter affecting economic sustainability).

These findings emphasize the need to explore various means by which the capital cost can be lowered (e.g. process intensification and process integration). However, the price of long-term wellhead methane can be significantly lower, particularly when SCP production is considered as an alternative to flaring (an operation that is often used to control methane discharge from refineries, fracking operations, coal beds, and bio-digestors). Such economic observations accentuate the need to improve SCP production's environmental performance to benefit from the forthcoming financial incentives used to combat climate change.

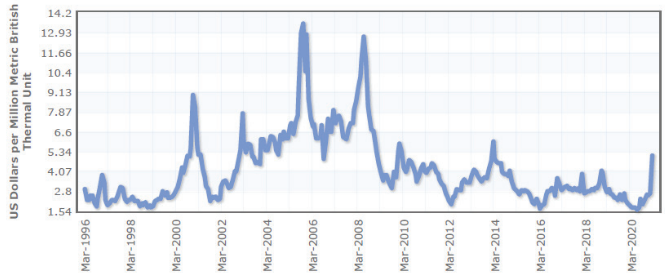

Fig. 17. Strong fluctuations in the price of delivered Natural Gas [5].

B. Environmental Benefits

The high-protein-content animal-feed ingredient produced by both technologies can be considered as: nutritious, affordable, safe, pesticide-free, traceable that can be used as a non-GMO, uses no arable land and almost no water in its production. Its production is also immune to seasonality or other undue climate influences (e.g., extreme temperatures, droughts, and floods). In some feed tests, certain unique nutritional characteristics, and extra health benefits, were observed. These factors could create some additional value for the animal feed formulators.

For example, the planned production rate for the Chongqing City plant (100,000 tpa) is estimated to [41]:

- Replace the fishmeal made by wild-catching 420-450 k tonnes of fish,
- Free up as much as 535 km2 of land used for producing soymeal, and
- Save nine million cubic meters of water.

However, with the present global concern about climate change, it is very possible that both positive and negative financial incentives may be imposed on businesses in order to accelerate the adoption of novel technologies and management approaches that can result in reducing GHG emissions. Depending on the overall environmental performance of the feed production approach, such incentives can significantly affect the financial sustainability of the production methodology. To address the additional uncertainty caused by this socio-political factor, it is necessary to have reliable estimates concerning the environmental impact of producing SCP that considers a wide range of technical/economic/ policy scenarios.

A good example of such an effort is the study conducted by the "Carbon Trust" (an organization that advises governments and companies on emission reduction), where several options for reducing the environmental effects of the food system were analyzed. Their report is based on industrial performance values and

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compared how much land is needed, how much water is used, and how much CO2 is emitted by the various feed production methods [55]. It found that when fossil-based methane is used for power generation and as a feedstock, the carbon footprint per tonne of feed produced is much higher than that associated with many other sources of protein. On the other hand, this can be reduced to less than half the original emission levels if biogas methane is used for feedstock and energy. This advantage is further enhanced by the fact that SCP production utilizes significantly less water than plant-based protein sources and does not take up any farmland [55]. The latter is very critical to the issue of rapid biodiversity decline.

This vulnerability is most probably one of the biggest reasons behind the observation that two major consortia presently involved in the industrial-scale fermentation of natural gas contain partners that cover the whole range of expertise needed to succeed in this emerging field (NG supply; Fermentation technology; process engineering, and animal feed marketing and utilization). For example, the consortium led by Calysta includes world leaders such as: BP Adisseo, Temasek, AquaSpark, Mitsui and Cargill; whereas that led by Unibio includes: Mitsubishi Corp. and Cermaq, where the latter is one of the world's largest salmon farming companies. By spreading the risks amongst all members of the end-to-end value-chain-wide consortia, it may be possible to improve the long-term food security and sustainability for the world's growing population.

However, the sustainability of this approach can still benefit from addressing the following issues:

- Promoting the use of bio-protein as an ingredient in formulated feed for farmed fish, crustaceans, poultry, livestock and pets, where the incorporation of bio-protein is known to result in measurable advantages to their growth/health. Thanks to the efforts by several agencies, it appears that the European Union has approved for including dried Methylococcus capsulatus (Bath) bacterium in the feed formulations for most animal and fish species [37; 56]. This may also result in commanding higher market value based on the superior performance achieved by SCP-containing formulations and/or their beneficial environmental impact.

- Most of the food safety and feeding tests were conducted using cold climate species. Therefore, it is advisable to develop a similar database for feeding animals prevailing in temperate/subtropical/tropical climes, where the market growth is projected to be higher.

- Significant improvement in the performance of fermentation systems can also be achieved by using process-intensification approaches [57- 60]. In the present situation, this is mainly achieved by enhancing the rate of inter-phase mass transfer in the bioreactor. This, in turn, enhances the rate of bioconversion and conversion efficiency while reducing reactant losses. However, growing concern was recently expressed about the need to carefully examine the fundamental relation between capital expenditures (CAPEX) and operational expenditures (OPEX) of intensified and non-intensified bio-based processes. In the current environment, where the emphasis is placed on reducing the environmental footprint of chemical and biochemical operations, there is a growing indication that greater importance should be given to OPEX minimization as a means for sustainable bio-economic development [61].

- Similarly, "Process Integration" is known to reduce the operating costs mainly by applying the concept of waste minimization to various process and energy streams [62 – 64]. In the case at hand, the potential use of methane-rich waste streams (such as those encountered in refinery flares, coal bed methane, fracking flares, biodigesters, etc.) would be natural candidates. Such an approach would be an excellent example of a win-win situation while racing to reduce carbon emissions across many fronts. Unfortunately, the typical scale of biodigestion operations is relatively small [65], rendering difficult the sustainability of such an approach.

VIII. THE WAY FORWARD

There is a growing worldwide concern regarding the approach being used to meet the present demand for protein, a nutrient that is essential for human health. This concern is exasperated by the large growth in demand projected for the next few decades and the growing awareness of the detrimental environmental impacts it has on land and water resources as well as the associated GHG emissions.

Springmann et al. [66] have recently analyzed several options for reducing the environmental effects of the food system, including:

- dietary changes geared towards using healthier and more environmentally-friendly diets,
- improvements in the technologies and management practices used, and
- reducing food loss and waste.

They found that no single measure is sufficiently capable of keeping these effects within all planetary boundaries. However, a synergistic combination of all possible measures will be is needed to sufficiently mitigate the projected increase in environmental pressures.

The approach proposed in this paper discusses the potential for adopting an alternative way for meeting the present and future demands in a sustainable fashion. It also presents means by which the economic and environmental uncertainties can be addressed, particularly when the gases, otherwise flared during oil and gas production and processing, can be used as a feedstock and/or source of energy. However, a significant R&D effort is needed before this approach is widely accepted.

ABBREVIATIONS

FAO Food and Agriculture Organization of the United Nations
FCR Feed conversion ratio
NESRC Natural Sciences and Engineering Research Council of Canada
tpa Tonnes per annum
UNEP United Nations Environmental Program
UTT University of Trinidad and Tobago
WB World Bank.

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