

# Assessing the Potential Role of Dark Fermentation of Waste Streams and Its Related Business Models in Future Circular Economy

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## ABSTRACT

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The global community is facing an unprecedented perfect storm battling with the Grand Challenge of climate change, with economic, societal and environmental ramifications being felt as much as never before, with South Asia at the epicenter. With greenhouse gas (GHG) emissions as the main driver of climate change, special attention is put into decarbonizing sectors that are the main contributors of these gasses. These include obvious ones, such as the energy sector, but also less obvious like waste. Nonetheless, numerous challenges lie on that end. For the former, intermittency of renewable energy is the biggest obstacle, whereas for the latter waste management and valorization are the key challenges to overcome. Dark fermentation has the potential to be the process that connects these seemingly irrelevant sectors through the solution of bio hydrogen. Hydrogen has been touted by many as the most promising alternative as an energy carrier and means of storage, primarily due to its energy density and lack of carbon content. Dark fermentation is applied both to municipal and agricultural waste, using easy to cultivate bacteria such as clostridium combined with E.coli. With the organic acids that remain, bio stimulants can be generated to benefit the rural communities, whereas with residue remaining from the lower hydrocarbon chains, useful bio methane can be channeled towards heating and cooking. This study initially examines sustainability, circularity and economic functionality of such a business model. It also assesses the implications, opportunities and challenges of a business model around dark fermentation for stakeholders, including farmers, distribution operators, energy storage companies and renewable energy communities. Finally, this study emphasizes on the public private partnership (PPP) possibilities and the strategies and policies. Multiple methods will be utilized, including empirical evidence/knowledge and literature research, but also interviewing methods will be included, if time allows, to the stakeholders involved, such as municipal workers, grid distribution/transmission professionals, regular citizens - members of renewable energy communities and farmers. The outcomes expected from this research are to identify the best and most cost-efficient dark fermentation practices, including the most cost-effective and least energy intensive byproducts, but also make a painstaking stakeholder map. In this way, the economic, social and ethical costs and benefits will also be identified.

**Keywords:** Fermentation, Waste Stream, Circular Economy

## 1. Introduction

Manmade climate change is creating the conditions for the complete degradation of our environment across all of its sectors. Firstly, it contributes to increasing extreme weather events, such as flash floods, forest fires and hailstorms (Raupach et al, 2021). These events, in turn, significantly affect the agricultural sector, changing production patterns that seriously influence food prices and production patterns. This entails great importance especially for countries in the Global South, with a focus in arid and semi-arid regions, where like in Yemen today in the 21st century we are seeing unprecedented famine across the whole country (Adams et al, 1998). Conventional agriculture which is the most common

worldwide has already depleted its soils of all nutrients and microorganisms with the overuse of pesticides, artificial fertilizers, which destroyed the biodiversity able to mitigate the climate change, and it is now by far the most unstable production chain in face of climate change. Foods produced this way have far less nutrients than their counterparts from the 1920s when the initial nutritional values were measured, and with further processing they are stripped of all micro and macro nutrients but carbohydrates and fats. These issues combined lead to severe health problems, which is a huge societal concern, such as “infectious and respiratory diseases and an increase in the mortality rate”(Rocque et al,

2021).

South Asia is expected to face the bulk of this devastation, as it is one of the most vulnerable regions to climate change. It is already among the world's most vulnerable regions to flood-related natural disasters and, since flood risk is sensitive to different levels of warming, these events are expected to substantially increase over the next few years, in particular in India, Bangladesh and Pakistan (Mirza, 2011). The region is expected to see their agricultural land shrink alarmingly and “face desertification more than most regions, resulting even in malnutrition and famine”(Jat et al, 2016). Just a quick glance at recent flash floods in Pakistan and we can clearly see the reality of these scientific claims coming to fruition. All of this will create the perfect conditions for the massive spread of diseases such as cholera, typhoid and malaria, which will have devastating effects on the people's livelihoods and health (Sen et al, 2017), without mentioning the food security which is already alarmingly high in the region. It is audibly delineated that it is of uttermost importance to address these issues in the Global South, with a special focus on South Asia, and decarbonize every sector, with the ultimate goal of mitigating climate change.

As climate change is anthropogenic, focus will be put on the decarbonization of two human activities that are responsible for the largest part of greenhouse gas emissions (GHG). On one hand, several scholars have asserted that the chief reason for the aforementioned emissions is the energy sector. The solution on that regard is found in renewable energy (RE) technologies and the main challenges related to that are contemplated to be the intermittency of several renewables, the feasibility of economic models that are “beneficial for the society and the lack of investments in the Global South” (Papadis & Tsatsaronis, 2020). On the other hand, waste disposal accounts for more than 10% of CO<sub>2</sub> emissions, because by placing it in landfills methane is emitted, which is as much as 4x more harmful than CO<sub>2</sub>. Currently, even in countries like the USA, more than half of it is disposed of in landfills, instead of seeing attempts to reintroduce it in the value chain and creating circularity. Conventional processes of waste valorization, such as coal gasification or the existing ways of aerobic wastewater treatment are deemed to be carbon positive and it is becoming increasingly complicated to push waste-to-energy processes to the socio-technical regime (Novotny, 2022). We as humans are the only animals on earth that do create waste and are destroying whole ecosystems in the process; therefore it is of utmost importance to stop,

rethink and regain control of our waste streams. Begin to see the value in our waste and reintroduce the circularity of nature into our economy.

The foregoing obstacles are very difficult to be overcome and a solution that would be able to tackle all of them, decarbonizing both sectors and at the same time addressing the decarbonization challenges of intermittency, economic feasibility and social acceptance in a holistic manner could create a new economy and revive the local communities which is particularly needed in the Global South.

## **2. The solution of dark fermentation for biohydrogen production**

Hydrogen has been championed as the most suitable energy carrier solution to cope with the intermittent nature of most of the renewable energy solutions and provide “a sustainable and clean approach to storage and transport of energy on a global scale”(El Ammam & Ozcan, 2019). Hydrogen has already been produced mostly for industry use, and there are several ways of producing it, from conventional fuels such as coal, oil and gas, but also from renewable sources, such as solar and wind. Over the past years, biomass is becoming an increasingly promising way of producing hydrogen as well, gaining traction as we move forward with the energy transition, with research studies on the different feedstocks being seen as “the sole scientific challenge at the moment”(Nikolaidis & Poullikkas, 2017). The main obstacle is mainly due to the fact that hydrogen production from biological processes has not been well-studied so far.

Out of the biological processes, dark fermentation is touted to carry out the biggest potential of creating a reliable and scalable source of hydrogen. It mainly consists of fermentation of both obligate and facultative anaerobes, in the absence of oxygen and light. The substrate for the process is chiefly composed of lignocellulosic biomass, carbohydrate materials like wastewater from industry, sugar-containing crop residues, and municipal solid waste(Kamran & Fazal, 2021). It can also include other types of biomass with a similar chemical composition, such as aquaculture products, namely micro- and macroalgae. Numerous species of both have been found to be rich in either proteins, carbohydrates or lipids, all of which are valuable feedstock for the dark fermentation process(Jacob-Lopes et al, 2020). Algae in particular would be an ideal type of feedstock, because it has been found that wet biomass has much greater potential as feedstock for dark fermentation than dry one(Dahiya et al, 2021).

The metabolic pathways that are considered the most suitable thermodynamically are the following:

- Hexose to acetic acid
- Hexose to butyric acid
- Acetate to ethanol

The third one is deemed to be the best option for hydrogen production (Sarangi & Nanda, 2020).

The end product of this process is a mix of H<sub>2</sub> and CO<sub>2</sub>, but also traces of CH<sub>4</sub>, CO and H<sub>2</sub>S are found in most of the mixes. The initial glucose, through the glycolytic pathways can be converted later to pyruvic

acid, which, in its turn, is then further converted to CO<sub>2</sub> and H<sub>2</sub>. The ratio of butyrate to acetate can highly determine the level of biohydrogen on the mix from glucose.

A table of the microorganisms and substrates that have been tried so far and the yields generated can be found in table 1. A pattern that can be comprehended in this case is that sugar-related products in general generate higher yields, which also highlights the type of feedstocks that would be good to be further studied.

**Table 1:** Microorganisms and substrates combination for biohydrogen production, and hydrogen yield. Data was retrieved from Jacob-Lopes et al, 2020.

Microorganisms	Substrates	Hydrogen Yield
<i>Caldicellulosiruptor saccharolyticus</i> DSM 8903	Hydrolyzed potato peels	3.4mol/mol
<i>Clostridium butysicum</i>	Sugarcane bagasse hydrolysate	1.73 mol/mol
<i>Clostridium saccharoperbutylacetonicum</i>	Cheese whey	7.89 mol/mol
<i>Clostridium thermocellum</i>	Wood Fibers	1.47 mol/mol
<i>Clostridium thermocellum</i> ATCC 27405	Sugarcane bagasse	109.6ml/g
<i>Clostridium thermocellum</i> 7072	Corn stalk	1.2 mol/mol
<i>Clostridium thermolacticum</i> DSM 2910	Lactose	1.5 mol/mol
<i>Clostridium thermopalmarium</i> DSM 5974 and <i>Clostridium thermocellum</i> DSM 1237	Cellulose	1.36 mol/mol
<i>Enterobacter aerogenes</i>	Glycerol	172.9 mol/g
<i>Enterobacter aerogenes</i> HO-39	Arabinose	120.9ml/g
<i>Enterobacter aerogenes</i> HO-39	Fructose	121.9ml/g
<i>Enterobacter aerogenes</i> HO-39	Galactose	118.2 ml/g

Enterobacter aerogenes HO-39	Galactose	118.2 ml/g
Enterobacter aerogenes HO-39	Glucose	124.5ml/g
Enterobacter aerogenes HO-39	Lactose	37.8ml/g
Enterobacter aerogenes HO-39	Maltose	140.7ml/g
Enterobacter aerogenes HO-39	Mannitol	206.8ml/g
Enterobacter aerogenes HO-39	Mannose	121.9ml/g
Enterobacter aerogenes HO-39	Rhamnose	69.7ml/g
Enterobacter aerogenes HO-39	Xylose	117.9ml/g
Thermoanaerobacterium thermosaccharolyticum W16	Corn stover	2.24mol/mol
Thermotoga neapolitana	Rice straw	68.2ml/g
Rumicoccus albus	Sweet sorghum residues	2.59mol/mol
Thermotoga neapolitana DSM 4349	Hydrolyzed potato peels	3.3mol/mol

During the process, positive standard Gibbs free energy is achieved, which means that there is no group of microorganisms that can result to a complete conversion of the substrate into biohydrogen. This means that byproducts are inevitable. The bulk of these comprises of organic acids and their utilization is the most promising means to make a biohydrogen-based business model truly profitable(Ding et al, 2020). The most common method involves further processing of the remaining acids into biohythane, a mixture of biohydrogen and biomethane(Sarangi & Nanda, 2022), but it is certainly not the sole manner and more profitable ones are going to be explored during this research, involving more stakeholders in the process

Nonetheless, bio-H<sub>2</sub> production still entails challenges related with the economic viability of

certain processes and their limitations. Taking this into consideration, there is great value in better understanding the sustainability, circularity, economic feasibility and scalability of such business models related with biohydrogen.

### 3. Assessing several indicators of a business model -LCA

Biohydrogen production from numerous biomass feedstocks, such as (in)organic waste, woody biomass, marine biomass such as micro and macroalgae essentially introduces novel business models. This primarily happens due to several reasons. Firstly, it is a fact that decentralized production will be prevalent in these energy sources, since biomass resources are numerous and it makes more sense in terms of transportation costs and emissions to move to such a model. Secondly, it can

introduce the notion of the biomass renewable energy communities, where certain facilities can gather the whole community's biomass, convert it into biohydrogen and store it for utilization or trade. This also creates the very interesting concept of the prosumer. A prosumer in the case of a biohydrogen economy can become more than an energy trader and actually can valorize the residue from the biohydrogen production or trade the valorized products, which adds additional dimensions to these types of business models. Lastly, as mentioned, the scalability can be severely affected by the type of biomass, so this also needs to be taken into consideration. Finally, after the foregoing assessment, a better comprehension of the role of each stakeholder ought to be created.

### 3.1. Circularity

The aspect of perfect valorization of all the waste(or other) biomass is the chief obstacle on the circularity of dark fermentation. Most studies have delineated that hydrogen conversion efficiency has not exceeded 60% through the utilization of any type of feedstock(Ghimire et al, 2015). It should be indicated that the aforementioned efficiency largely depends on the type of feedstock and that substantial improvements have been made, considering that less than a decade ago the efficiency of dark fermentation combined with photofermentation was 34%(Xia et al,

2013). Currently, as mentioned, applying dark fermentation to biomass can result in a 40% remaining residue, which can be valorized through coupling with biorefinery in different products, ranging from soil amendments to platform chemicals. Reflecting on the end product value, a certain preference is expected to be made towards the platform chemicals industry, which is a very promising bio-based industry(Becker et al, 2015). Recent research has shown that biorefinery can have a degradation efficiency of more than 60%(Liu et al, 2021), which still leaves a 16% of the residue going to waste. It is an eminent need that biotechnological advances reach the socio-technical regime and that their costs fall rapidly over the next years, so that such promising techniques can become affordable for local communities of the Global South. A working pattern that can have revitalizing effects on these communities are open-source hardware, living labs, citizen science and crowdsourcing models. By leveraging the crowds' strengths, true Renewable Energy Communities can be created and thrive.

### 3.2. Economic Feasibility

Economic feasibility is a major component of each clean technology process that aspires to be introduced into the Global South local communities. A breakdown of several techno-economic analyses that have been made can be found in Table 2

Table 2: Techno-economic analyses of a biohydrogen plant

Research	CAPEX	OPEX	Revenues from H2 per year	Revenue from FW per year	Profit per year	Capacity	Raw material
Han et al, 2016(1)	443100	366700	516400	58400	176885	10ton/day	Food Waste
Han et al, 2016(2)	318800	122920	66278	10950	-45691	10m3	Molasses
Li et al, 2012	-	91000	80000	12000	1000	10m3	Wastewater
Li et al, 2012	-	99000	19000	3000	-77000	10m3	Agricultural waste

Chang & Hsu, 2012	220000	29230	27000	50000	47770	10m <sup>3</sup>	Wastewater
Bonk et al, 2015	74.4mln	12.2mln	400000	21.6mln	7.8mln	1 ton	Solid waste

It should be mentioned that the final revenue largely depends on the FW further valorization. Both Li et al(2012) and Han et al (2016(2)) assume its conversion solely into CO<sub>2</sub> and that has two main components that need to be addressed. First, it does not discuss their conversion into platform chemicals. Second, the prices of CO<sub>2</sub> have skyrocketed ever since 2016, hence it can be argued that the financial losses that have been calculated do not reflect the present CO<sub>2</sub> prices and the technological advances that have been made ever since.

### 3.3. Scalability

In order to enhance scalability, the inhibiting factors need to be mapped. Rittman & Herwig (2012) stressed that the key culture parameters that need to be increased with that regard are “H<sub>2</sub>/S ratio, methane evolution rate (MER) and qH<sub>2</sub>”. Another important factor encompasses finding the “optimal enterobacter anaerobes”(Rambabu et al, 2021), meaning the ones that have can generate the highest hydrogen yield or that have the highest growth rates

### 3.4. Societal Acceptance

The lack of a full-scale elaborative life cycle analysis to this date is also the chief reason for the potential backlash such a technology might face in terms of societal acceptance. Moura et al(2022) point towards “toxicity dispersal and resource availability, primarily water”, as the main elements that might inhibit such a technology being accepted from society and in the case of dark fermentation, several of these can have a negative impact. Overall, hydrogen technologies have generally faced backlash due to issues related with the gas's probability of explosion and the potential NO<sub>x</sub> emissions that can severely affect its environmental impact. In addition, the fact that this process leaves by-products can be conceived negatively from the local communities, if no capacity building takes place beforehand. Another aspect that ought to be taken into consideration is the coupling with the biorefinery factor. As biorefinery is already being perceived with skepticism(Marciano et al, 2014) due to notions revolving around the fact that one should not meddle with the natural landscape and

nature in general, the potential for lack of acceptance is augmented.

For this reason, it is of uttermost importance to combat this by creating capacity building mechanisms that focus on the economic impact of such business models for each stakeholder. Also pointing out the great advantages which come with a circular approach to producing hydrogen and to general utilization of green hydrogen as a transitioning alternative to both fossil fuels and electric vehicles, as well as the climate mitigation potential of implementing such a round up approach. It is this very reason that a thorough stakeholder mapping practice must take place, identifying all stakeholders' key strengths, deficiencies and main benefits that they possess in this process, so that it can be conveyed to them in the optimal manner.

## 4. Stakeholder mapping

In the case of the emerging biohydrogen economy, a new type of interaction between state and private actors, public private partnerships, but also interaction with nature is bound to take place. In such cases, several human stakeholders are expected to be largely interested in services and goods provided by this ecosystem. Linking these goods and services and mapping the stakes that these players have on them is essential if we are going to have “effective, equitable and sustainable ecosystem governance and management”(Raum, 2018), because in this way it is understood who is part of this system and what is their actual involvement. Thus, in this chapter, a mapping of all relevant stakeholders will take place, presented in the end via an interest-influence matrix.

### 4.1. Waste Collection Utility/Company - Landfill

Companies and utilities related to the collection of waste have very clear objectives with regards to waste valorization. This lies within the waste reduction on the landfills, as in most countries globally there are issues related to overcrowding of landfills. Hence, their interests within a biohydrogen economy lay as a provider of raw materials. This means that it is in their best interest both to comply with national/

international regulations on circularity, but also to make endeavours to make profit from providing these materials to the biohydrogen labs/facilities. The primary challenge in these stakeholders' cases is having the financial capacity to pre-process/separate waste so it can then be used by the biohydrogen plant in an optimal manner.

#### **4.2. Wastewater Company or Municipal Sewage**

Wastewater companies/municipal sewage position in the ecosystem is similar to that of the aforementioned utilities. Their objectives and interests are more related with minimizing the waste that is disposed of and they will attempt to also achieve substantial gains from selling the wastewater. In this case, there is great interest to see whether wastewater or solid waste (and its different types) generate higher yields. As well as for whom it could generate higher profits when introduced into the circular hydrogen economy, as per today we have many wastewater processing plants that do sell humus as final product for gardeners, and this is usually the case across dry regions where its availability is scarce. Therefore will dark fermentation provide higher yields in biomass and further increase the scale of humus or alternative soil amendments? This has great importance as there might be competition with their solid waste counterparts (or other biomass providers). This means that there should be discussion over whether this new biomass market will be regulated or free, depending on the local (or national) governance models and religions. Similarly to the solid waste actors, managing to pre-treat wastewater is the most complicated task for them.

#### **4.3. Municipality**

The municipality's main objective is mostly to achieve sustainability and circularity for its citizens' livelihoods. Their chief interest as part of a biohydrogen economy is to ensure that it runs smoothly, in a fair manner and that certain standards of quality of the different processes are met (from processing of the biomass to its utilization). However, the most important aspect is correlated with the financing part. Each municipality's interest to ensure that there is adequate public financing to support such biohydrogen initiatives is the top priority. In terms of means used, this entails:

- Coordinating with regional and national governments and with international institutions (UNDP, USAID etc) to secure financing resources for its citizens.
- Working together with adjacent municipalities to create cooperation schemes. For example, rural-

urban partnerships can create a great tandem, leading to energy and other products' trade.

- Creating a regulatory and legal framework to support clean hydrogen fair trade that will be inclusive for all groups of people within the community

- Increase demand for hydrogen by retrofitting their existing vehicles (e.g public buses and cars) to running on hydrogen

The most difficult work for the municipality will be to create the framework/provide the incentives in a correct manner that ensures circularity and eliminates emissions, given the fact that the people working there will require capacity building for the new economy.

#### **4.4. Renewable Energy Community (REC)**

The RECs objectives and interests are similar to the municipal actors' ones, but have a more technical approach. Their main objective is energy management is optimized in the community and that storage options optimize the facilitation of this management. It is in their best interest to maximize profits for its prosumers, both economic and environmental, and to distribute these profits in the best manner, generating gains for the local community/society as well. The means that they can deploy are:

- Organize a REC framework, that creates a clear roadmap on how the REC will function, how trade will other RECs/the grid will take place

- Coordinate with the local municipality and the international institutions to express the REC's needs in terms of financing and to inform the interested parties about where these funds will be allocated

#### **4.5. Microloans, micro creditors and similar agencies subsidizing green alternatives and their adoption**

Microloan providers and microcreditors will be acutely important in the case of small-scale biohydrogen power plants. They can mobilize funds of up to \$100,000 and hence they could fully fund the whole power plant. Their objective is to generate traction for a green economy (such as a biohydrogen economy) on a small-scale and also create profits for themselves, essentially such as most financial institutions. The means that the pursue are:

- Providing microloans to RECs/biohydrogen plant operators to buy equipment

- Coordinate with international institutions to create a broader financing scheme for biohydrogen communities

The most complex situation that microloan providers will have to face is structuring the loans themselves, given that many stakeholders will be involved in the production process of biohydrogen, so equipment will need to be purchased by many of them.

#### **4.6.NGOs and other non SMS non government players advocating for diversifying of green alternatives.**

NGOs in the field of clean energy technologies have a clear objective: to facilitate the adoption of such technologies by the broader population. This means that they are interested more than anyone to make people knowledgeable on the technical, economic, societal and ethical aspects of, among other technologies, a biohydrogen economy. The means they can deploy involve:

- Raising awareness campaigns
- Providing workshops on technical/economic skills on hydrogen - Capacity building of municipal workers/sewage and solid waste workers in the optimal separation of biomass and other relevant and important skills

They will unfortunately have to face the lack of societal acceptance towards hydrogen due to claims about its explosive nature or due to other assertions about how clean energy from biomass actually is. But as it is their mission to spread awareness and contribute to wider knowledge dissemination, it will be their role to dispute the claims and reassure populations on its benefits through different approaches such as hands-on workshops, integrated management of a communal hydrogen power plant, or other approaches similar to introducing regenerative farming in conventional farming communities, where resilience towards any other way but conventional farming, was built through generations.

#### **4.7.Energy Storage Companies**

Companies that manufacture and/or operate hydrogen tanks want to maximize their profits or, alternatively, see the demand being maximized. Their interest is to see a booming biohydrogen economy and their main challenge is to be able to provide such options at affordable costs and at small-scale. Their main means are:

- Invest in R&D for the optimal solutions for biohydrogen RECs at low costs
- Work together with NGOs to raise awareness on safe storage of hydrogen
- Lobby/promote the biohydrogen REC concept within local, regional and national governments

#### **4.8.Distribution Operator**

The DSO main objective is to facilitate the transition into a micro- and smart grid electrical system. Hence, their interest in biohydrogen in that regard is that it becomes a key player in storage and management within microgrids. What they can do about it is mostly coordinate with RECs, so that biohydrogen is managed and stored in a manner that maximizes profits for its prosumers, without at the same time overloading the grid or making an acute increase in the electricity/energy costs.

#### **4.9.Hydrogen vehicles manufacturers**

Retrofitting garages and car manufacturers see enormous value in this innovation, as this will result in a spike in need for new vehicles/retrofitted vehicles. This is their best interest in this case. The best way to express their interest and pursue it within a biohydrogen economy is by raising awareness in the local communities and coordinating with the government on creating financial incentives for owners of such vehicles. This can happen at a national level if big players such as car manufacturers are involved, or at a local level, if hydrogen retrofitting garage owners are included. In addition, these stakeholders can incentivize the local community by themselves, by providing easier payment schemes in installations with low(or zero) interest,

#### **4.10.Smallholder farmers**

Farmers are similar to waste-related stakeholders, in the sense that they possess the raw materials that can later be converted to biohydrogen. However, their interest lies not so much on being compliant with environmental regulations, such as the sewage companies, for example. Their interest in this case is maximizing economic profitability by utilizing agricultural materials that would otherwise go to waste. Another potential reason for interest is the utilization of hydrogen to power their vehicles, namely their tractors and relevant equipment. By gathering in associations, they can leverage their collective power and request from public state actors (e.g municipalities, ministry of agriculture) to provide them with incentives to increase the circularity aspects of their businesses. These can be achieved through numerous actions, such as buying out the agricultural waste from the farmers associations, or offering subsidized/ free retrofitting of their vehicles and further subsidized hydrogen for the duration of their contribution in the circular chain.

#### 4.11. Other agencies working on rebuilding the town-village link

In this business model, a new type of partnership will emerge: the rural-urban partnership. This will encapsulate farmers and waste(water) utilities sharing their waste streams and retrofitting companies of tractors and buses sharing best practices so that end-users convert to hydrogen. Their harmonic and best co-existence is in the best interest of new emerging agencies that will be working on rebuilding the link between urban centers and rural areas. Their biggest challenge, at the same time, will be to show if and how such a business model will work and how will the new types of public-private partnerships (PPP) , such as the farmers-waste(water) utilities one would actually function.



**Business Models**

There are many possible business models in a circular economy that involve green hydrogen. Here we will try to explain two such models interlinking the hydrogen usability and future circularity between the city and a village. As mentioned in our stakeholder map and throughout the chapter, we can use municipal waste streams as well as sewage and agricultural waste to produce green hydrogen using dark fermentation. This gas further gets distributed locally and increases the retrofitting of buses and other public transportation vehicles in the cities for example, while increasing the retrofitting desire for tractors in the villages, which could be incentives by local governments or subsidized. These further make the hydrogen more available at the local gas stations making the phasing out of the fossil era into a regenerative one more effective, faster, safer and readily available.

As there is no need for manufacturing the brand new cars or vehicles, all can be retrofitted in a similar fashion as petrol engines are being retrofitted today in any Joe's garage to methane or natural gas. The second link is the residue after fermentation which can be processed into soil amendments for agriculture, increasing the soil productivity and leading to greater yields and providing for future agricultural waste. Looking into the storage question, hydrogen is a fuel so there is no need for lithium batteries, meaning no mining and all the other CO2 expensive activities related to new battery productions. Also old fossil fuel storage cells can be refurbished into Hydrogen ones.



**Business Models**

#### 4.12. Main takeaways of the business models

All these will create the space for phasing out of fossil fuel economy faster and give space for electric vehicles to develop more sustainable battery solutions and conversions, giving us a buffer to not have to fall on fossil fuels again, like we are falling today from gas to coal and other much more destructive fuel alternatives when it comes to heating the Europe due to the current political situation. As for EVs we still need heavy duty machinery to dig for lithium, and the whole chain of production is heavily dependent on fossil fuels, as creating a fully new vehicle is today. However if we create a new rounded hydrogen value chain, it will not only secure the ultimate safer transition to EVs phasing out of fossil fuels, as it will allow for us not to bank everything on one single modus of powering but allow for diversification which has proven again and again to be the safest bet. 7 Conclusion

As climate change is induced and intensified and amidst its catastrophic consequences for rapidly growing regions like South Asia, the energy transition will require many more “weapons” to become efficient and truly protect the environment and people. One of the relevant technologies that are very promising is biohydrogen production through dark fermentation and valorization of the residue organic acids. There has already been research that has provided extended information on the expected hydrogen yield based on the waste valorized, however there are limitations, as all types of biomass can participate in the process. Additionally, economic analyses have had severe limitations, as they do not account for the myriads of uses the residues from the dark fermentation process can have, which can significantly increase the revenue generated. This research has great value in light of the Indian presidency in the G20, where the agenda includes more RES implementation, increasing regional interconnections and scaling-up storage and energy management technologies. A biohydrogen economy touches upon all the foregoing topics and hence should be endorsed, both financially and in terms of legal/regulatory framework, by state actors in the Global South, so that all of its potential benefits can be distributed to the stakeholders involved.

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