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Renewables for Green Transition: A Policy Insight for Adoption of Technology by Consumers

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ABSTRACT
The present research presents how a decentralized biomass to hydrogen energy production technology can generate rural welfare and reduce carbon emission in mining operations. A literature survey is undertaken for renewable energy application in mining and biogas to hydrogen production. The research aims to show how consideration of human factors can lead consumers to adopt right technology and sustainable practices in construction and mining. Through a comparative study of possible technology deployed in green transition we position this technology of biomass to hydrogen energy production. The article discusses the present government policies and suggests policy changes to effect change and social welfare. It also highlights how this technology can be strategic to rural growth and relevant risks associated in its implementation.

Keywords: Renewables, Green mining, Biomass, Hydrogen, Human Factors

BACKGROUND

The world has changed significantly over the years. In his book "The philosophy of social science", Martin Hollis recalls his jaw dropping experience of 1980s when, on switching the television he could watch the news about the communists' regimes of Eastern Europe collapsing while the Soviet Union stood alone and to then his utter awe; which he describes as "utter impossible"- *there was no Union of Soviet Union Republics!* As we venture towards the year 2026, we have seen various such collapses akin to Martin Hollis's experience. The world trade center terrorist attack of 2001, the Iraq war of 2003 to overthrow Saddam Hussein's Regime, the financial collapse and sub-prime crisis in America in 2007-2008, the Covid-19 pandemic of 2020, the ongoing Russia – Ukraine War of 2022, the war of Israel in West Asia, tariff wars and recent political regime changes in Sri Lanka, Bangladesh and Nepal. The macro [1]events that shaped geopolitics in the past were political and financial in nature. The future challenges will be a ripple effect of these, but what we shall encounter, even with more severity, will be related to natural disasters. The world's thinkers and leaders have sensed this, and climate change has been addressed in various forums. A great concern of all nations is *sustainability*. The net-zero targets set by both developed and developing countries are worthy of mention. The impact of green mining is of extreme importance here.

While the fall of the Soviet Union was identified with the failure of communist philosophy, many argued that it may not necessarily be true, or in other words, we may say *appearances can be deceiving* (Hollis, 1994). Many scholars argue that the theory of Karl Marx is still valid, as the Soviet Union and its hegemony in Eastern Europe were not what socialist theory preached. So, if the theory was never tested, how can one refute it? Theorists who believe in the bipolar structure influencing the world may argue that the fall of the USSR only made way for a new power to take its place, and many say it is China. While this was happening, a large energy company in the US called Enron filed for bankruptcy under Chapter 11 in the USA in 2001. This opened a can of worms, exposing the rampant capitalist collusion and corruption. In the same year, the terrorists attacked the World Trade Center. Does this then indicate that even the capitalist theory is failing? If one did not believe so, the subprime crisis exposed how the corruption was there in all layers of American society, the epitome of capitalistic theory.

All the above undesired situation witnessed by mankind is possibly linked with the greed for power of a few people who wish to control the larger society, but inadvertently lead to the collapse of both the socialistic and capitalistic approaches of society building. With the increased interconnectedness and ease of communication globally through social media, mankind is witnessing a new way of global consensus on priorities. The attention required by global leaders for "sustainability" of the global society is shifting from the limited consideration of a "country", a political construct that came into existence around 200 years back. Consideration of "sustainability" will remain a central principle to take any long-term policy decision by the global leaders in any area, including our current topic of discussion, "Green Transition".

The world leaders have witnessed all this and are now introspecting on how to fill the vacuum created by a failed communist power and a failing capitalistic structure. In other words, after the thesis and anti-thesis, it's time for synthesis, to which the answer is *sustainability*. An important role to be played here is that of policymakers.

INTRODUCTION

As we can see, "sustainability" has become a principal consideration in policy making for country leaders, it is influencing many areas of society such as "environmental", "socio-cultural", "ecological" & "political", which are primary areas linked with our current article. We are increasingly observing divergence of opinion between "developed" and "developing" countries on necessary action required from "developing" countries to reduce carbon and other toxic gas emission in the environment causing long term damage to the ozone layer of planet earth as the former is responsible to damage it from the period of industrial revolution in 1700's and the later is currently getting the fruits of economic prosperity with increased industrial activities.

Economic prosperity of a country will require energy as a primary driver, and developing countries with financial constrain will be going for cheap energy sources of power through coal mining. Although coal mining will have an impact in the long run on all the areas of "environmental", "socio-cultural", "ecological" & "political" aspects of society, in this article, we are proposing some solutions for the problem of "environmental" damage due to the use of fossil fuel for operating the machines in the coal mines. Green transition in mining is needed to reduce the gap between the developed and developing countries on the carbon emission issue, which we expect will lead to better cooperation and sharing of other Green technologies with the "developing" countries at an affordable price by the "developed" countries.

When we mention sustainability, we are countered with a fight between the developed and developing nations. There has been a debate for ages about reducing emissions and achieving carbon neutrality. While this could be done rapidly if we close all sources of carbon emissions, like thermal power plants and carbon-intensive industries like mining, this option is impractical. While mining has become economically unviable in many developed countries due to the high cost of labour, their proposal to close down mines has been opposed vehemently by developing and underdeveloped countries. The latter contends that the poor state of the present climatic condition is a result of pollution caused by factories operated in the rich and developed countries in the last 100 years. These countries operated the steel plants, power plants, etc., and became rich by polluting the world. Technology has improved over the years, and the present plants are much efficient and less polluting; however, the climate conditions have become drastically worse. The rich nations amassed wealth in the past, and when it is time for the developing and underdeveloped countries to grow, these rich nations are citing future deterioration of the climate, and hence impeding the growth of the emerging nations. This tug of war is never-ending. As a result, the underdeveloped and developed countries are not closing the carbon-intensive plants, while the rich nations and not owning their past acts by sharing their wealth with the poor nations to subsidize expensive green energy. When this is seen through the lens of the world structure described in the article, we can see political motivations behind such fights.

Green mining can be a solution to end such fights. The underdeveloped and developing countries, if given a cheap way to produce energy, will not lean on carbon-intensive energy-producing methods. In fact, the problem is not with *carbon* per se but emissions of carbon, which are depleting the ozone layer of the atmosphere. Hence, if we have technologies to reduce emissions or eliminate emissions, there will be no objections from rich countries. But this also makes the present processes of energy production economically expensive and sometimes unviable. The other way is to absorb the carbon within the process, i.e, carbon sequestration, and hence eliminating emissions. In this parlance, we will introduce the technology of Bio-mass to hydrogen energy conversion technology and how this will be a social revolution and rural development, a sustainable energy solution. We propose to use this technology to drive mining. However, before we present our concept ecosystem, we shall introduce green mining.

LITERATURE SURVEY

(Pekka, 2017) describes how Finland has used Green Mining to engage communities and add value to society by minimizing waste and maximizing local benefits. He mentions how mining is opposed by people with a perception that it is damaging to society and the environment, but do not reduce consumption of mineral-based products, and how Green Mining can be a tool to overcome this. (Qian, M, Miao, X, and Xu, 2007) study coal economics and green mining in this sector. (Dutta et al., 2016) explain how rare earth elements (REE) are crucial to the renewable energy sector and green mining strategies to address this dichotomy. (Z. Zhang et al., 2022) present a model to capture greenhouse emissions in the goaf, thus helping green mining by resolving the dual problem of pitheads left by coal extraction and greenhouse gas impacting the climate. (Herrington, 2021) debate the level of acceptable supply of cobalt and lithium for a sustainable green future. The author explains the importance of these metals as critical to the green revolution; hence, the question is, how much should we mine? This is an important direction, and (vsrsrangasai, 2017) what Swami Vivekananda cites as *Everything Excess in Life, Is Poison"*.(Terry C. Cheng, F. Kassimi, 2016) Study the impact of tailings on environmental damage and technology gaps to tackle this problem.(Guozheng, 2018) Bring out the definitions of green mining and the difference between green mines. The paper segregates green mining into the processes of green exploration, reclaiming, production, the green mining area, green financing, and green tourism. The author explains the hurdles and policy changes required to effect green mining. (Ming-yin et al., 2009) use game theory to analyze the government's incentive to implement green mining. It also models market incentives and technical incentives. (Jiskani et al., 2021) present a framework called green and climate smart mining (GCSM), which has 6 leading indicators viz waste management, pollution, energy and resource consumption, technology enablement, environment protection, and strategic and managerial efficiency. (Shi, 2012) brings out the trichotomy of resources mining, environmental protection, mining area sustainable development, and calls it the closed energy cycle material feedback process. The author highlights balanced relational mining area development for sustainability and multi-dimensional and multi-angle requirements of green mining. The author highlights the importance of biomass energy as a critical need due to the depletion of fossil fuels.(Stanković et al., 2022) present a model to use green energy from wood and straw biomass, and biosorption to purify water

We thus see that biomass-to-hydrogen energy can be a strategic technology in green mining. We will now elaborate on the technology present in this and how this may bring social growth.

Biomass to Hydrogen production – Gray and green hydrogen

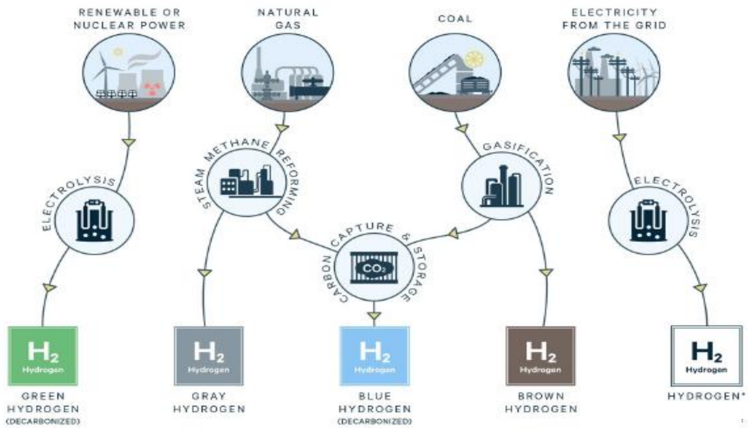

Figure 1: Hydrogen by color

Hydrogen is a clean fuel that, when consumed in a fuel cell, produces only water. Hydrogen can be produced from a variety of domestic resources, such as natural gas, nuclear power, biomass, and renewable power like solar and wind. Hydrogen is an energy carrier that can be used to store, move, and deliver energy produced from other sources. Today, hydrogen fuel can be produced through several methods. The most common methods today are: thermal process i.e, natural gas reforming, Coal gasification, Biomass gasification, Reforming of renewable liquid fuels and electrolysis. Other methods include solar-driven and biological processes. (National Grid, 2021) There are various types of hydrogen categorized from Green to Pink in a spectrum. Green hydrogen is that produced without any greenhouse gas emissions usually from water with electrolysis using green energy like solar or wind. Sometimes term yellow hydrogen is used when using solar power. Blue hydrogen is produced from natural gas by a process called steam forming and involved carbon capture and storage, Gray hydrogen the most economical at present is produced from natural gas or methane by a process called steam methane reformation but without capturing greenhouse gases. Black hydrogen or brown hydrogen is produced by gasification using coal. Pink hydrogen is produced from nuclear energy source by electrolysis. Turquoise hydrogen is produced by a process called methane pyrolysis and involves carbon capture.

(Ramesh, 2022) introduces a technology developed in IIT BHU by Scientist Dr. Pritam Singh. Thermally-accelerated Anaerobic Digestion (TAD) Technology, introduced by Biezel Green Energy Pvt. Ltd. involve a novel fractionation process that extract Hydrogen (3-4%), Methane (12-14%) and bio-Tar (2-4) % by weight from bio-waste and convert it into smokeless bio-coal (25-28%). This fractionation process has almost 50% mass-to-fuel conversion efficiency. The TAD process is almost 5-7 times more efficient than any biomass-to-fuel conversion process existing in the world. The entire process can be completed by electricity generated from the byproducts received during the process. Dr. Pritam Singh and Dr. Konda Shiva are students of Prof John Goodenough of the University of Texas, Austin, the 2019 chemistry Nobel laureate. The article cites Dr. Singh, "that the TAD reactors in 36 hours can process 2 tons of biomass to produce various products including hydrogen, methane, bio-coal and liquefied natural gas." The cost of such hydrogen produced is less than $5/ kg. However, if the other byproducts are successfully sold, hydrogen may also be sold for free! The news article also cites R&D Director SSV Ramakumar of IOCL biomass gasification as "the only way" to produce hydrogen at $4-$5 /kg. The cost of electricity is $0.074 to $0.101 /kWh (Global Petro Prices, 2022). The diesel price is Rs. 89 to Rs. 95 /lt. (Molloy, 2019) Hydrogen's density is 120 MJ/kg, thus producing 33.6 kWh /kg, while diesel is 45.8 MJ/kg, thus producing 12-14 kWh/kg.

Table 1: Energy V/s price

Sl No	Energy	Calorific Value MJ/kg	kWh/kg	$/kWh	Rs. Price/ kWh
1	Electricity(Coal)	25-19	8.14	0.074 – 0.101	Rs. 5.9 - 8
2	Diesel	45.8	12-14	0.101 – 0.120	Rs. 8.9-9.5
3	Hydrogen	120-150	33.6	0.112 - 0.148	Rs. 9.07- 11.2
4	Lpg	46	12.78	0.072-0.08	Rs. 5.83- Rs.6

The process of producing hydrogen by the biogas TAD reactor is given below:

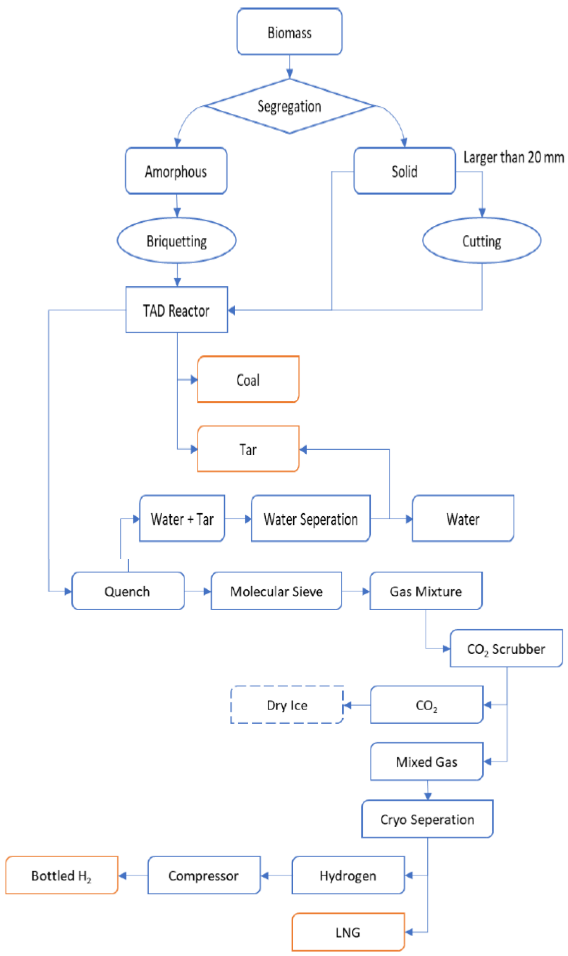

Figure 2: TAD process for Biogas to H2

(Gupta & Gupta, 2014) provide a method to recover with anaerobic digestion unused coal from the abandoned mine in the form of biogas, which will be used as useful energy. The above is a green mining initiative.(Szewczuk, 2015) provides a case for the use of this gas in the transport sector as fuel. These are useful when we discuss the ecosystem for the biomass to hydrogen plant in green mining.(Yin et al., 2022) discuss blending methane gas with biogas to achieve a concentration good enough to produce electricity. The article mentions the low concentration of less than 10% and hence inefficient for use in the available methane at coal mines. However, when blended with bio-gas, this becomes useful. This further adds to the portfolio of options to produce electricity by cheap means at mining sites.(Nethengwe et al., 2018) highlight potential uses of biogas as a green energy. The article describes biogas as a gas rich in methane and a green source for electricity production. The article describes digesters used to produce the gas. This will be critical when we describe the ecosystem we propose in our article.(Bedoić et al., 2019) The article describes how agricultural waste is used to produce biogas. (Nahar et al., 2017) discuss the advances so far in different processes of hydrogen production from biogas and how hydrogen fuel cells are superior to internal combustion engines.(Hosseini et al., 2015) study the various methods of biomass to hydrogen production. They mention the case in Malaysia and the waste of palm as a cheap feedstock. The methods mentioned are biomass pyrolysis, supercritical water gasification, which can produce hydrogen at $0.89/kg to $1.5/kg and 0.35/kg, respectively, much lower than that by PV Electrolysis, which is $2/kg to $4.2/kg.(Pal et al., 2022) discuss the biomass and hydrogen production techniques and the hurdles in this path. (Nath & Das, 2003) discuss the state of technology in hydrogen from biomass, it compares the merits and demerits of these processes.(Kırtay, 2011) categorizes the processes in thermochemical and biological processes, and also the biomass-derived fuels to be used in producing hydrogen.(Turner et al., 2008) describes the various routes being explored by NREL (USA) to achieve a goal of $2-$3 /kg for hydrogen.(Kırtay, 2011)

clarifies that hydrogen is not a primary energy source, but a carrier or secondary energy source like electricity. The authors highlight that it can be produced from many *primary energy* sources and how eco-friendly biomass may replace fossil fuels as the energy source to produce hydrogen.(Sanchez et al., 2021) do a technical and environmental analysis for hydrogen production from sugarcane residuals and find 56% efficiency. They highlight that this residual can diversify energy sources from rural areas. This is important as we can take it to be a money generator in rural areas. (Levin & Chahine, 2010) discuss the challenges in producing hydrogen from renewable sources and how a decentralized mode is preferred to centralized production.(B. Zhang et al., 2021) The author provides a source and uses of hydrogen, which we depict below:

Table 2: Supply V/s Demand

Supply/ Sources	Demand/ Uses
Nuclear, Nuclear electricity Hydro, Solar, Wind- Electrolysis Solar Thermal Biomass	Turbines, IC Engines, Process, Poly-generation Fuel cells- Buildings, FC Engines Transport- FC Engines

The article further explains how hydrogen is not freely available in nature and hence we need to produce it from water or carbohydrate disintegration. The article mentions that at present 96% is produced from traditional fossil fuels. Thus, this is only shifting of the problem or risk shifting, as we shall elaborate later. The article compares the various sources of production and states how biomass is a better option due to its large reserves, high annual output, and easy oxidation. The article misses out on the value added to the rural economy, which we shall highlight in the ecosystem we present.

The drawback, it says are complex and ungradable derivatives after hydrogen production. They recommend selective conversion of biomass to chemicals and oils and thus reducing production cost. We have seen that in the TAD process described earlier, this is converted to methane, dry ice, high-calorific-value coal, etc. The article then compares it with the electrolysis process, where the energy consumption is the hurdle. The energy required to break the covalent bond needs electricity, which is produced from coal-based sources, thus putting it in jeopardy. Further, the cost of less is more than that of hydrogen, thus making the process economically unviable. However, when instead of water, coal slurry is used, the electricity consumption drops, but this is still expensive, says the article.

Another difficulty is the rare earth material used to make the electrodes. This is the second jeopardy and a circular feedback problem. Thus, the use of low-carbon alternatives like Ni is the way out. Hence, even here, green mining is needed to produce the hydrogen. The article provides a comparative table adopted from below:

Table 3: Comparison of the costs of capital and hydrogen production of various methods

Process	Energy source	Input Feedstock	Capital cost (M$) Range		Hydrogen cost ($/kg) Range	
			Min	Max	Min	Max
Biomass pyrolysis	steam	agri	3.1	53.4	0.25	2.2

Coal gasification	Fossil fuel	Coal	435.9	545.6	1.34	1.63
Indirect bio-photolysis	Solar	Water +	135		1.42	
Auto-thermal reforming	Fossil fuels	Natural gas	183.8		1.48	
Methane pyrolysis	steam	Natural gas	–		1.59	1.7
Biomass gasification	steam	Woody	6.4	149.3	1.77	2.05
Process	**Energy**	**Input**	**Capital**	**Hydrogen**	**Process**	**Energy**
			Min	**Max**		
Steam methane reforming	Fossil fuels	Natural gas	180.7	226.4	2.08	2.27
Direct bio-photolysis	Solar	Water +	50 $/m^2		2.13	
Nuclear thermolysis	Nuclear	Water	39.6	2107.6	2.17	2.63
Dark fermentation	–	Organic	–		2.57	
Photo fermentation	Solar	Organic	–		2.83	
Nuclear electrolysis	Nuclear	Water	–		4.25	7
Solar thermal electrolysis	Solar	Water	22.1	421	5.1	10.49
Solar photovoltaic electrolysis	Solar	Water	12	54.5	5.78	23.27
Wind electrolysis	Wind	Water	500		5.89	6.03
Solar thermolysis	Solar	Water	5.7	16	7.89	8.4
Photoelectrolysis	Solar	Water	–		10.36	

It also gives the emissions and energy consumption figures from

Table 4: Indexes of various technologies

No.	**Hydrogen-production technology**	**Equivalent greenhouse gas emission [(kg, CO_2)/(kg, H_2)]**		**Energy consumption [MJ/(kg, H_2)]**	
		Min	**Max**	**Min**	**Max**
1	Coal gasification	5000	11300	190	325
2	Natural gas	3900	12900	165	360
3	Solar	2400	6800	30	80
4	Wind	600	970	5	12
5	Biomass	400	5600	4	20
6	Nuclear energy/thermochemistry	300	860	360	410

The shift of carbon footprint rather than eliminating carbon emission in green solutions

(Gibson et al., 2017) debate the ecological impacts of solar, wind, and hydro, and possible mitigation strategies. It concludes wind as the least risky and hydro as the most risky. Also, polysilicon production is not viable because of the high cost of electricity in India. Hydro dams produce substantial emissions and GHG gases, according to the author. (Maeroff, 2020) reports that this so-called green energy is actually a misnomer. She reports that biofuels, supposed to be green, are causing deforestation and also emitting greenhouse gases. The author also criticizes the solar and wind sources, citing Germany, where 48% of the renewables came from wind turbines, which consumed 230 T of steel, which requires a huge amount of coal. If the world consumed 25% from wind power, it would require 600 million MT of coal. Also, it notes that the maintenance of the wind-powered plant needs fossil fuels. The article mentions how solar panels have a significant carbon footprint. The solar panels use quartz, which needs mining and 4 tons of tetrachloride waste for every ton of polysilicon produced. The article also comments on the inefficiency of energy-producing plants like solar and wind.

In line with the above article, we may reflect on India. In a country like India, political considerations are also critical, and when it comes to solar, most raw materials are imported from China; such dependency is not sustainable. Furthermore, the disposal of solar panels, which shall cover huge landmasses, will be a great concern, and the electronic waste produced will be hazardous.

We thus see that what we call green energy is actually shifting the carbon from one industry to another. As the article cited above mentions about steel being used to produce the wind turbine, we also see that while you transport the material to build the plant, you also use petrol. Thus, transportation uses GHG emissions. We thus shift the carbon from the power plant to the logistics. To assess the net reduction, we have to calculate: carbon footprint in construction of plant + carbon footprint in disposal of plant + carbon footprint in operation of plant –reduction in carbon footprints in operation of plant.

In the case of electric batteries, we find a similar dilemma. The cars running on EV batteries do emit less GHG than the petrol cars, but we have to add the carbon footprint in making the battery (rare earth material, mining, supply chain) and disposal. Thus, we see that

Another term that comes in this parlance is greenwashing. This is a term used to misguide consumers into believing that the product is environmentally friendly. The risk shifting is thus quite evident in greenwashing.

Risk shifting is a term popular in capital structure when we discuss debt and equity structure, and when agency costs go up, when a company gets in trouble, and equity holders shift the risk to debt providers. If we consider fossil fuels as debt and renewable energy as equity, we need to consider how much risk we are shifting to other sectors when we produce green energy.

India’s strategy to integrate rare earths, hydrogen, and biomass reflects a broader push for self-reliant clean energy. The National Critical Mineral Mission (India’s Critical Mineral Mission, 2025) is securing rare earths for magnets, turbines, and electrolysers and reducing depency on imports of rare earth, while the National Green Hydrogen Mission (₹19,744 crore outlay) targets 5 MMT annual green hydrogen production by 2030. Within this, biomass-to-hydrogen pathways are emerging as a vital complement: India generates over 750 million tonnes of agricultural residue annually, much of which is underutilised or burnt. Converting this into hydrogen through thermochemical gasification or advanced bio-refinery processes can both cut emissions and provide a decentralised, indigenous hydrogen source. Rare earth magnets and catalysts are critical in the equipment that drives biomass gasification, electrolysis, and hydrogen storage, linking the two domains.

Gaps persist, however, in scaling up biomass-to-hydrogen technologies beyond pilot plants, ensuring feedstock aggregation and supply chain logistics, and developing cost-effective catalysts and separation technologies (where India still depends on imports). Policy integration between rare earths, biomass utilisation, and hydrogen remains fragmented; a coordinated framework could unlock synergies by tying rural biomass supply chains to hydrogen hubs, supported by critical minerals for the machinery.

Mining with Green Energy – Electric battery-driven trucks, viz H2 Driven trucks

The Mining industry has a general consideration that as the size class of machines becomes bigger, the per-ton cost of coal production becomes cheaper. To operate bigger machines with very high energy requirements, we are currently using diesel-powered engines in the machines or electric-driven motors getting electricity from the Grid. We see two sources of carbon emission – fossil fuel burned in an engine or Electricity produced in Coal coal-fired power plant. Alternative fuels are such as LNG or bio-diesel, are being promoted through Govt. policy drive and commercial benefit to the mine operators; however, the scope of expansion is constrained by many other factors, and it also does not provide a long-term solution, it only reduces the carbon footprint at the current high level.

Therefore, we need to look for a solution which will consider all major aspects of society as was stated earlier - “environmental”, “socio-cultural”, “ecological” & “political”. It also requires a cyclic approach where there will be interdependency of all the stakeholders to ensure the Green Solution being implemented is sustained in the long run.

Use of a hydrogen-driven engine fits into the above criteria as we have technology available today where high high-capacity engine can be driven using hydrogen as fuel in those big mining machines. Moreover, India is blessed with a lot of biological waste generated locally. We can produce green hydrogen locally using this biological waste, and also with the investment coming into the locality, driving the local economy, and helping the economic upliftment of local people. One of the major sources of socio-political instability in India has been the movement of people from one region to another due to economic considerations, bringing in the socio-political unrest in the locality. Development of the local economy benefited by all stakeholders, Mine owners, local people, and Govt, with better bio-waste management and lowering of carbon emission, and local job creation will ensure long-term sustainable solution.

Proposed Ecosystem

The proposed ecosystem tries to reduce risk shifting and uses the feedback loop to the advantage of green solutions in mining.

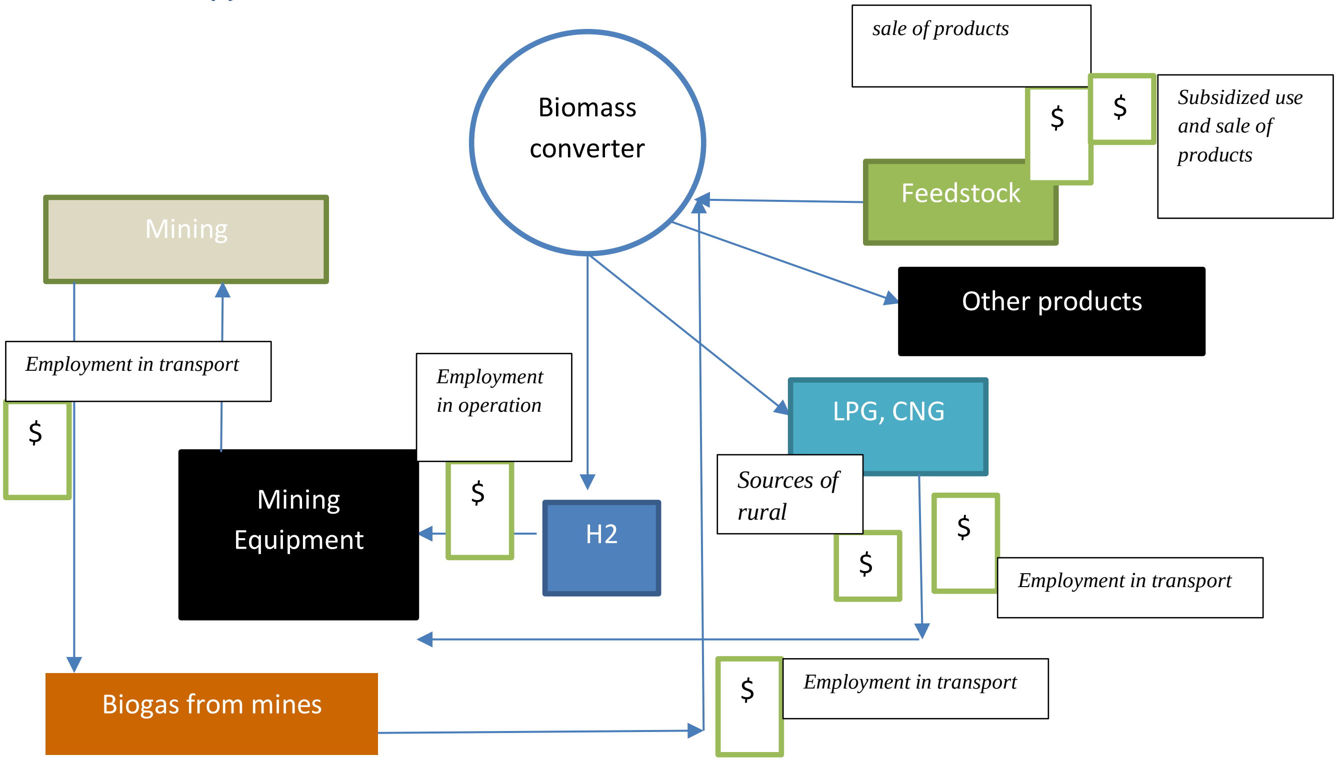

Figure 3 : Ecosystem with associated cost points

System Dynamics Model

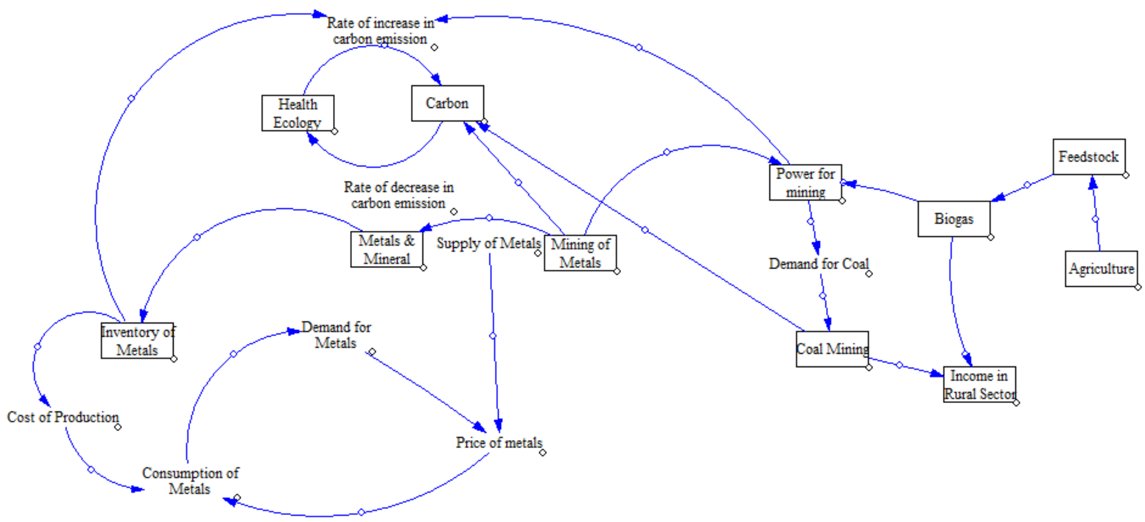

Figure 4: System dynamics model representation

SDG 13 goals, Composites and H2 technology

(United Nations, n.d.) provides 3 targets including strengthening reliance and adaptive capacity, integrating climate change indicators in policies, improving education, etc. Our present article provides directions in all these areas. To further emphasize and provide actionable steps, the green hydrogen and application of composites would be practical steps. In line with these goals (Raja Ghosh, Sarojkant Singh, 2022) provide a method to route finances for green energy subsidizing with CSR initiatives, and how this can also be utilized as a risk mitigation measure. (Sarojkant Singh, 2022) present a framework for policymakers to utilize a systems approach to handle climate change risks. This supports the SDG 13 goals and could be very impactful in the context of the present research.

Two of the most commonly used methods for generating hydrogen are using solar energy – Photoelectrochemical (PEC) water splitting - and electrolysis. In comparison to the traditional process, composite materials can enhance the sustainability of PEC water splitting by improving the efficiency and durability, reducing material consumption, and enabling eco-friendly alternatives of key components. As an example, photovoltaic (PV) panels are produced through an energy intensive process. Lightweight composite back sheets can replace traditional polymer or glass options, reducing the overall weight of the panels. Similarly, carbon fibre or fiberglass composite frames offer a durable alternative to aluminium frames, maintaining structural integrity while further minimizing weight. Advanced composite polymers are also being employed as encapsulation materials, providing superior protection and stability for PV cells while allowing for greater flexibility in design and form.

Green hydrogen generation through electrolysis splits water into hydrogen and oxygen using electricity. This process involves metals and other components that can be energy - and carbon-intensive to produce. The environmental implications primarily arise from the materials used in the electrodes and membranes of the electrolyzers, the energy-intensive manufacturing process, and their mining and refining processes. The question then is, is green hydrogen really "green"? Composite materials overcome this major flaw by enhancing the efficiency, durability, and scalability of key components. In electrolysis systems, they are used in membranes, separators, and housing to resist corrosion and improve ion flow. Their lightweight, corrosion-resistant properties replace heavy metals in structural components, while advanced composites doped with non-precious metals serve as alternative catalysts, reducing dependence on rare elements like platinum and iridium. Composites can also be engineered for superior conductivity and thermal stability, extending the lifespan of electrolysers and minimizing replacements. With advances in manufacturing and recyclability, composites lower the overall carbon footprint of electrolyser production and operation.

Limitations and Future Research

The article provides a general description above of the model, and needs to be validated with numbers through a simulation and practical implementation. The article also needs further research to indicate how much time it may take to implement, what the minimum scale to be implemented in practice is, and what amount of investment is required to start a cycle of economy based on green hydrogen. The causal diagram shown in the article is to be implemented with results in a system dynamics model software. Further research on policy formulation is required, and incorporating CSR initiatives for green mining. Validation of the model with simulation and a practical project.

CONCLUSION

The article provides a conceptual framework for the implementation of green mining and a comparison of presently available resources for the production of energy. The framework shows how green mining can use biogas as a source of energy to reduce carbon footprint and make the use of hydrogen energy as a fuel for mining activities. It is evident that the challenge of using hydrogen is only hindered due to the cost of hydrogen, and as a biogas plant has several by-products, the sale of these can be subsidized to generate hydrogen, which needs a policy to make this possible. Further, composites shall play a crucial role in reducing the cost of hydrogen fuel. The project takes center stage when analyzed with a focus on human issues and social welfare being enabled with such a project. Such an ecosystem will eliminate the need of rare earth minerals and raw material sourcing from China.

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