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Article

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Reference: Gupta, Bhumika/Sen, Salil K. (2019). Carbon capture usage and storage with scale-up : energy finance through bricolage deploying the co-integration methodology. In: International Journal of Energy Economics and Policy 9 (6), S. 146 - 153.
http://econjournals.com/index.php/ijeep/article/download/8104/4643.
doi:10.32479/ijeep.8104.

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2019, 9(6), 146-153.

Carbon Capture Usage and Storage with Scale-up: Energy Finance through Bricolage Deploying the Co-integration Methodology

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Received: 03 May 2018 **Accepted:** 15 July 2019 **DOI:** https://doi.org/10.32479/ijeep.8104

ABSTRACT

Recent studies surprisingly indicate that fossil fuels could constitute 81% of primary energy demand, to 2040, 60% would continue to be from coal. This could mean more greenhouse emissions. This paper addresses the research proposition that coal though black, yet, could be green with co-integration of carbon capture and storage (CCS) and carbon capture and usage (CCU). The incertitude surrounding the future of coal is a palpable and credible research gap. The other research chasm is the search of energy finance necessary to economically, societally and environmentally leverage the carbon removal. This issue is addressed as bricolage finance for optimal resource optimization. The bricolage supports societal entrepreneurialism that deploy funding sources from bottom-up developmental finance. The twin key outcomes here are: (i) Appropriately scaled-up, grassroots-sourced bricolage sustains the societal acceptance of CCS and CCU, (ii) enhances the environmental economics of coal-based thermal power plugged-in with CCU and CCS. The methodological essence of this approach is tri-trajectory literature review, that propose (i) technology-led CCU/CCS (ii) financial derivative based bricolage and (iii) economic recalibration through bottom-up approach for community-level buy-in. Practical application of this framework is probed with instances from less developed regions in Asia, Africa and Latin America. The data draws from published reports on coal-intensive habitats, particularly in developing countries. Pattern coefficients and reflective indicators were deployed to predict, monitor, and reorient support or opposition for CCS implementation.

Keywords: Energy Finance through Bricolage, Carbon Capture and Usage, Carbon Capture and Storage, Pattern Coefficients, Reflective Indicators
JEL Classifications: Q01, O35, R580

1. INTRODUCTION

This paper roots for carbon capture and storage (CCS) and carbon capture and usage (CCU) with emergent energy bricolage finance builds on co-integration (Ozturk, 2010). Bricolage finance interwoven with CCS and CCU presents a convincing growth hypothesis (Acaravci, 2010). Carbon capture removes carbon dioxide from emissions emanating from fossil-fuel based energy infrastructure. CCS and CCU, a constituent of negative emission technologies, may reduce overall emission costs, thereby creating bricolage finance viability (Grivins et al., 2017). Co-integration solutions are increasingly gaining acceptance in climate-energy policy dilemmas (Tjernshaugen, 2011). The future of coal presents a structural-cognitive challenge for smooth adoption of CCS coupled with CCU (Pillai et al., 2017). CCS and CCU sways partisan beliefs to surge toward innovation and transition for a clean environment while retaining fossil-fuel based thermal power (Frankwick et al., 1994). This paper posits three key issues for co-integration (Huhne, 2016), (a) emerging innovations in the domain of CCS and CCU (b) deployability of bricolage (c) energy finance scale-up. These are elaborated in the literature, methodology and discussion sections. The following paragraphs outline the architecture of this paper.

1.1. Emerging Energy Innovations for CCS and CCU

Anabolic assimilation of global warming emissions utilize chemo-litho-trophic living organisms to transform carbon dioxide to value-added materials, such as polymer biodiesel and bio-plastics (Thakur et al., 2018). Mineral-trapping with micro-organisms rapidate CCS. Herein, the dissolved carbon dioxide gets precipitated as carbonate. Another approach is solubility trapping of carbonate in solution. Micro-organisms perform bacterial hydrolysis of urea. The latter could be scaled-up for deep subsurface CCS sites (Mitchell et al., 2010).

1.2. Deployability of Bricolage for Optimal Resource Mobilization

Given the abundance of coal, particularly in less-developed and developing regions of the planet, institutional financing mechanisms on nascent technologies such as CCS and CCU, are not readily forthcoming (Desa and Basu, 2013). Simultaneously, social entrepreneurship is gaining momentum with the resource dependence theory (Preffer and Salancik, 1978) complementing the conditions of social entrepreneurship for CCS and CCU. Bricolage is primarily locally sourced that has high likelihood to curb exchange rate risk impact thermal energy firms diversely (Kandir et al., 2015).

1.3. Energy Finance Scale-up

Integrated analysis of scale-up needs to assess the relationship between financial performance and environmental performance (Munawaroh, 2018). At least twenty countries have working pledges to slash greenhouse gas emissions by 40% by 2030 compared to 1990 levels. For instance, it is significant for a state, such as California, to commit to 100% clean energy (Ring, 2019).

2. LITERATURE REVIEW

Assorting and recombing available resources at hand is bricolage (Baker and Nelson, 2005). Waste to resource utilization powers the dynamics of social bricolage (Di Domenico et al., 2010). Value creation in communities (Kulothungan et al., 2019), opportunity recognition and entrepreneurial bricolage with respect to carbon harvest (Guo et al., 2016) support the cause of cleaning coal-based emissions. This is corroborated by environmental retrograde impact on environment, healthcare, and economic development (Anwar, 2012). The current review prospects on emerging innovations that can improve environmental quality, including the potential for coal-based thermal power with CCU and CCS. Indeed, coal has many irremediable limiting factors, as configured in the sustainability pentagon concept to cut carbon footprints (Madichie and Kolo, 2012). However, coal's widespread availability, economic feasibility, and geologic widespread presence often tips the scale in favor of quick-fix energy solutions (Kalayci and Hayaloglu, 2018). The challenge of public acceptance is key to embedding a positive image towards innovation and transition to CCU and CCS (Ahmed, 1991). This is true for coal-intensive habitats, particularly in developing countries (Fernando, 2014). The present review was inspired by pattern coefficients and reflective indicators for predicting, monitoring, and reorienting support or opposition for CCS implementation (Warren et al., 2014). There are ingrained attitudes with respect to potential risks and benefits associated with CCS and CCU (Bradbury et al., 2011), and pattern coefficients and reflective indicators assess the innovator–deterrent equilibrium with respect to community approval/disapproval of the potential benefits vis-à-vis dangers associated with CCU and CCS (Coltman et al., 2008). Here, the implementability of a coal future based on CCU and CCS is examined through tangible benefits to the local economy, such as creation of new skillsets and livelihoods with respect to a CCU and/or CCS facility in the vicinity (Van Alphen et al., 2007). Practical implementation of a coal future by retrofitting CCS and CCU as a viable portfolio composition on each energy mix is suboptimal (Scheer et al., 2013). Back-to-back aligned and integrated CCS and CCU facilities can significantly reduce emissions from coal-fired power plants as well as the production of steel, cement, and chemicals. Currently, 15 large-scale CCS projects are being mainstreamed, with six more poised for 2018. Using a tri-trajectory literature review to substantiate the implementability of CCS and CCU, the current review analyzes pattern coefficients and reflective indicators with respect to the following antecedents: (i) Incubation-stage technology, (ii) risk-laden financing, and (iii) adequate community-level buy-in. The "in tandem" framework for CCS and CCU was then configured to assay pattern coefficients and reflective indicators with respect to innovation and transition of the prospective CCS/CCU-based coal future.

2.1. Literature on Co-integration and Relevance of the Structural-cognitive Theory

Structural cognitive modifiability is a potent theory that explains possible acceptance of CCS and CCU at the community level (Feuerstein et al., 2002). According to relevant literature, the theory of structural-cognitive modifiability serves as cognitive junctions to mediated co-integration that progenerates relationships, such as resources optimization and carbon farming with CCS and CCU. Learning propensity develops that in turn generate community acceptance (Feuersvin, 1990). Guidelines revisiting the basics of CCS and CCU are necessary to determine how to mainstream CCU and CCS to impact a carbon-remedied coal future. Cement, steel, refineries, high-carbon electricity generation, and petrochemical plants need transformative changes with respect to a carbon-remedied coal future. Various applications of coal, such as coal-based thermal power, biomass, gas, oil, and related others, serve as inputs. The common denominator is the undesirable output (or fallout) from these flows: Greenhouse gas (CO_2, NOx, H_2S, etc.). Carbon capture initiatives can harness both flow trajectories, transit of resources, waste, as well as processing of inputs. Natural gas infrastructure is plugged-in with carbon capture for geological storage of CO_2. Gas is also tapped for domestic and industrial usage. The predominant issue is the CO_2 and related higher greenhouse gases that emanate from the operations, processes, transits, supply chains, logistics, and energy–waste–waste processing. CCS and CCU present a single enabler of quantum reduction in greenhouse gas emissions. Given the nascent and emerging technology, financial viability, and societal safety considerations, a tri-trajectory literature search was conducted herein.

2.2. Literature to Support the Methodology and Tools: Pattern Coefficients and Reflective Indicators

Revisiting the concept of pattern coefficients and reflective indicators, they were deployed to ascertain antecedents of the co-integration derived research construct. The structural construct in the present review relate to reflective and not formative measures of carbon-remedied coal with CCU together with CCS. Such latent relationships are corroborated statistically by assessing the covariation between latent constructs and observed variables or indicators of the latent constructs (Borsboom et al., 2003). The latent factors affect the potency with respect to incubation-stage technology, risk-laden financing, and community-level buy-in; the objective is to confirm them as reflective indicators (Henseler et al., 2009). Latent constructs exist independent from the measures used even though the parameters share a common theme, as a carbon-remedied coal future is consistent with CCU and CCS. Pattern coefficients interpret the structure and communality of the beta weights for community responsiveness to CCS and CCU, the investor orientation to risks of financing, and the developmental stage of the incubation technology (Coltman et al., 2008). The literature which supports reflective indicators and pattern coefficients articulates and characterizes (i) incubation-stage technology, (ii) risk-laden financing, and (iii) inadequate community-level buy-in (Figure 1).

3. THE RESEARCH CONSTRUCT

Net-zero or net-negative emission-based coal futures (Rafiee et al., 2019) is the intended research outcome (Figure 1). The research construct is based on appropriately-scaled CCS and CCU embedded energy from coal (Goulder and Hafstead, 2017). Two sets of determinants navigate the co-integration. The pattern coefficients determine the structural challenge towards societal entrepreneurialism (Zainol et al., 2019). The reflective indicators lead the cognitive challenge to incorporate CCS and CCU to energy infrastructure from coal (Merven et al., 2017). A pertinent assumption here is that transition and innovation of the prospective coal future is essentially sector specific (Tarancon and Del Rio, 2007). For instance, iron and steel followed by chemical industries are top sectors in terms of coal-based energy consumption for highly production-intensive countries (Pavitt, 1984). This leads to environmental fallout in the form of CO_2 emissions (Ershad Hussain and Haque, 2019). Coal-based energy consumed by the chemical industry emits toxic pollutants, greenhouse gases,

Figure 1: Research construct schematic

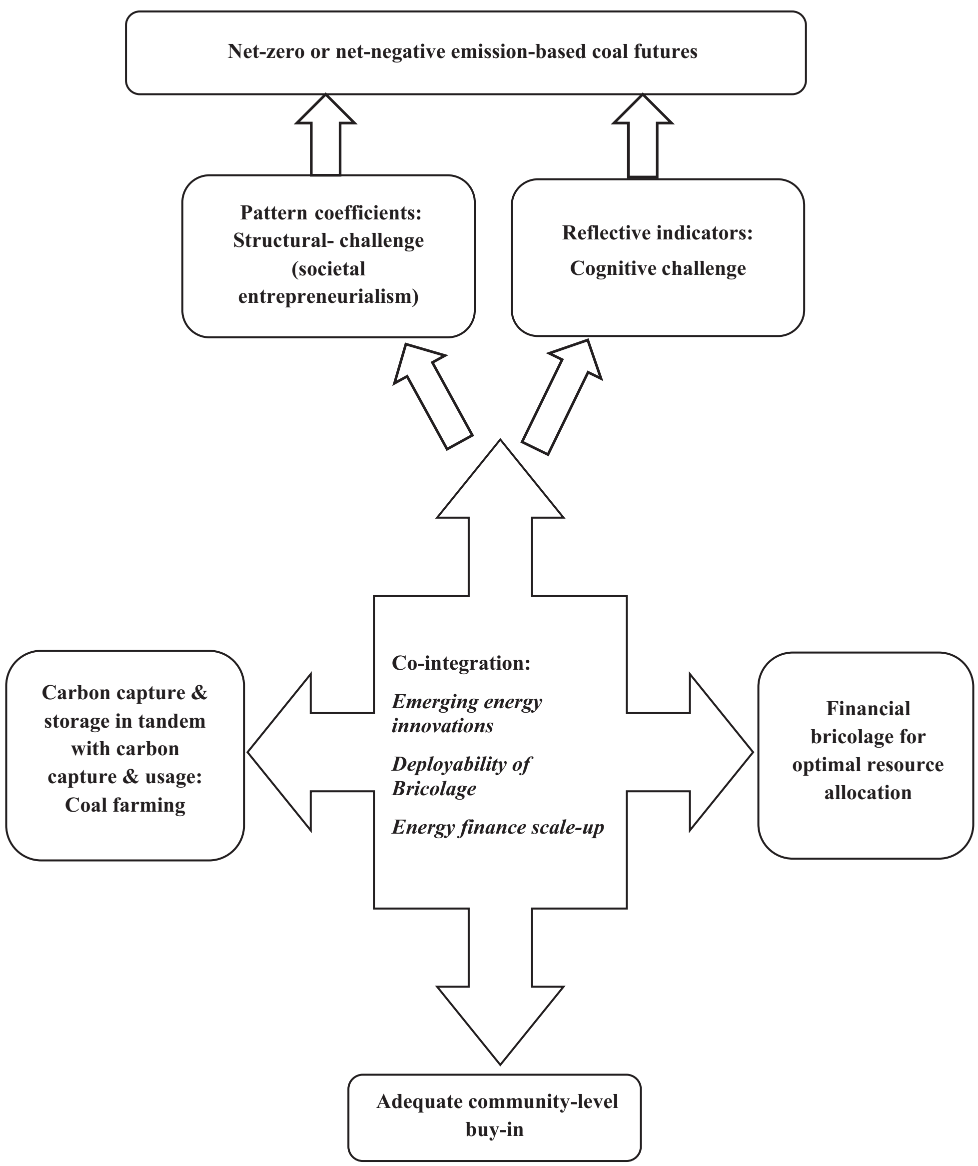


Table 1: Crafting a practical innovation pathway for a carbon-remedied coal future

Reflective indicators: Pattern coefficients	Carbon capture and usage	Carbon capture and storage	Carbon-remedied coal future in tandem with CCU and CCS
Technology incubation for sustainability in operations management	Uncertainties and issues for storage developers	Communicating risks	Bioenergy with CCS (Gough and Upham, 2010) Multiple uncertainties (Jin et al., 2017) Structural adjustment (Lesbirel, 1991)
Risk-proof financing mechanisms	Accelerate establishment of a CCUS financial security system	Incentivizing increase in storage and usage	Legal and regulatory framework (Valentić, et al., 2016) Capital and carbon (Beamish and Biggart, 2017)
Community-level buy-in for sustainable operations and supply chain	Development of international CCS and CCU safety standards	Leasing of land for surface and subsurface usage for marine and terrestrial areas	Multiple sector engagement (Markusson et al., 2012) Communicating risks (Bradbury et al., 2011) Cultural icons and urban development (Kong, 2007)

SO_2, nitrogen oxides (NOx), as well as wastewater. These issues underscore the emergent need for a pragmatic coal future policy that encompasses transition, innovation, and sustainability. The geo-spatial reach of sector-specific coal-powered energy.

4. METHODOLOGY

Co-integration methodology with pattern coefficients and reflective indicator tools chart the progress of assessment with respect to emerging energy innovations, deployability of bricolage (Schwandt, 2007) and energy finance scale-up (Coghlan and Brydon-Miller, 2014) (Figure 1). This is discussed in the following sections.

4.1. Coal-farming Technology Incubation: CCS in Tandem with Carbon Capture and Usage

In the current literature trajectory, indispensable pattern coefficients and reflective indicators related to incubation-stage technology process options are ascertained. Enhancing the cost metrics by correlating chemical properties of the coal-based feedstock led to a cost quantum by incorporation of CCS with options for CCU (Višković et al., 2014; Valentić et al., 2016). There is evidence on smaller percentage of coal finance (Lesbirel, 1991). There is evidence that many other banks are prepared to support cleaner and more efficient high-efficiency low-emission coal technologies, especially in Asia. About 100 million tons of coal-based combustion products are estimated in Europe alone, and CCU is being practiced in the coal industry and as coal-based combustion products are being used as building materials (Feuerborn, 2012). Absorption-based carbon capture processes utilize bulk volume, wherein atoms, molecules, or ions are dissolved in a bulk phase. Unlike absorption, adsorption adheres to the surface. Absorption is regularly deployed to treat industrial chemical processes to shed acidic gases, such as CO_2, H_2S, and NOx. In the case of adsorption, fluids with mixed liquid and gaseous mixtures adhere to a solid surface, the adsorbent. Cryogenic distillation and membrane separation are other CCS and CCU technologies. The latter is comparatively low cost and suitable for moderate purity gas streams. Flue gases, common in process industry, utilize amines as absorbents for membrane separation, while cryogenic distillation uses low temperature air separation. In the latter case, gases, such as CO_2, are removed through condensation. Cryogenics enable cost cutting in supply chains as transportation, storage, and operations are in liquid condition. Other productivity gains are water-neutral processes, where no chemicals are necessary and corrosion is avoided. Pattern coefficients and reflective indicators are deployed to predict, monitor, and reorient support or opposition for CCS implementation. Pattern coefficients provide a robust rationale through estimated empirical assessment of the analysis for the veracity of CCS in tandem with CCU for carbon-benign coal futures. To determine the correlation matrix between carbon-remedied coal variables, observed variables, incubation-stage technology, risk-laden financing, and inadequate community-level buy-in, linked with the factor loading pattern coefficient matrix of unique contribution of each factor to the variance in a variable, is established (Tabachnick and Fidell, 2013. p. 621).

4.2. Financial Bricolage for Optimal Resource Allocation

Providers of project finance, funding agencies, and commercial banks in Asia, such as Japan, Korea, and China (Gough and Upham, 2010), are supporting CCS through indigenous high-efficiency low-emission technologies. This funding reduces the impact of new policies of Western public agencies. The development of international standards for CCU and CCS with respect to safety are starting to develop. This is an important step towards enabling buy-in from private sector project developers looking to lower risk and augment assured returns. Risk perception is positive when disaster preparedness and safety assurances are incorporated. There are also elements to strengthen the financial incentives mechanism (Cleveland, 2009). The incubation approach (discussed in the preceding section) is relevant as CCU and CCS tandem pilot projects can demonstrate financial viability and sustainability. Techno-economic analysis for CCS with CCU project deals with sensitivity analysis of reflective indicators, such as CCS and CCU capitol, fuel, operation, and maintenance costs, and retrofitting for carbon-remedied coal (Jin et al., 2017). The direction of deviation is a challenge as this is a case for ungrouped data. It is proper to transform variables to normality, as such transformations may improve the veracity of a practical innovation pathway for a carbon-remedied coal future. It is necessary to ascertain whether the variable is normally or near-normally distributed after transformation (Tabachnick and Fidell, 2013. p. 86). After a distribution is normalized by transformation, the skewness differs in terms of direction and skewness type. In cases of positive skewness, the long tail is on the right, while for negative skewness it is on the left. In this case, the inadequate community-level buy-in demonstrates a negative skewness. This is remedied with reflective indicators which reflect the variable and then apply the transformation for positive skewness.

4.3. Energy Finance Scale-up for Adequate Community-level Buy-in

Public perception maintains health hazards and vulnerability to disasters near the carbon capture set-up. Societal acceptance levels are usually low (Beamish and Biggart, 2017). As a result, saline aquifers and depleted hydrocarbon reservoirs are presently selected as set-up locations. However, given the quantum of the land area (surface and subsurface, terrestrial and marine) locales need to be added (Koornneef et al., 2010). A key implementation gap is the issue of secure storage along with minimization of risks to the environment and human health. Recent literature describes development of a typology for their transformations in organizations working toward sustainable solutions (Gauthier and Gilomen, 2016). Society, government, and corporations are interdependent in their needs but differ with respect to possible solutions. Society corroborates acceptance based on the type of policies that are needed to protect the environment (Poumadère et al., 2011). The pattern coefficient and reflective indicator parameters are gauged here to enable the community to make informed and educated sustainable coal future decisions. There are several instances of infrastructure projects stalled due to societal pushback (Kong, 2007). The community consensus on coal projects can be reoriented through dissemination of CCU as well as CCS (Wolf and Ghosh, 2019). A key outcome of the present review is to configure the pattern coefficients and reflective parameters that would influence approval from society and instill confidence that the necessary precautions to protect the environment and those around it will be taken.

5. OUTCOMES: NET-ZERO OR NET-NEGATIVE EMISSION-BASED COAL FUTURES

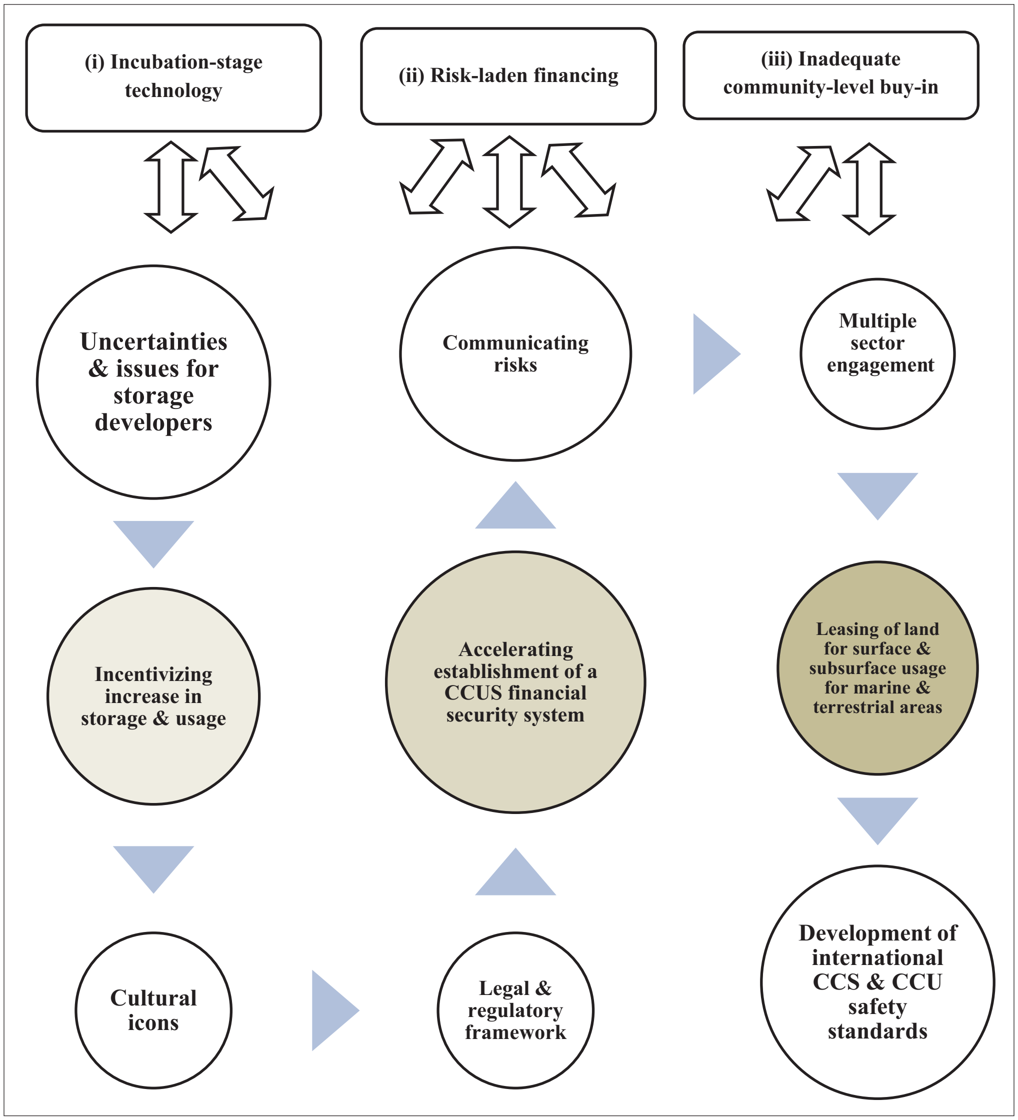
Innovation for sustainable development is augmented by underlying factor scores on incubation-stage technology, structure coefficients for risk-laden financing, and communality coefficients for community-level buy-in (Goodwyn, 2012). These findings help craft a practical innovation pathway for interpreting pattern coefficients and reflective indicators to enable a carbon-remedied coal future with CCS leveraged with CCU. A key pattern indicator of the present review is the potential for job creation. It is estimated that CCS with CCU would generate jobs and consistently sustain beyond 2030 to the scale of oil and gas industry. Indicators in standard confirmatory factor analysis models are endogenous, and the factors are exogenous variables that vary and covary (Kline, 2015). This aspect of a carbon-remedied coal future is assessed through the perspectives of incubation-stage technology, risk-laden financing, and community-level buy-in reflective indicators (Kotter, 2015). Community-level buy-in is codependent on the job distribution across sectors, chemical, process engineering, equipment manufacturing, pipeline and construction projects, and others. Such factors combine into a pattern of CCS and CCU-induced transport, storage, and distribution infrastructure. The likely pattern is subsector clusters around the carbon-remedied coal premise. This would utilize proliferation of appropriately scaled CCS units and captured CO_2 pipeline network. The higher the pattern coefficient, the more pronounced the exogenous reflective indicators, such as risk-proof financing and investment, would be. Scaling constants that assign a metric to each factor or pattern coefficient and reflective indicator are actualized from the combined emphasis of the triad of parameters: Incubation-stage technology, risk-laden financing, and adequacy of community-level buy-in. This approach is parametric simulation-based and analogous to the levelized costs of fuel, investment, and electricity and the cost of CO_2 avoided (Rao and Rubin, 2002). A parametric simulation-based approach lets the cost of capital, price of fuel, CO_2 and energy tariff assigned to a probabilistic range (Rubin et al., 2007). Figure 2 depicts the findings in the form of a pathway, namely, incubation–stage technology, risk-laden financing, and community-level buy-in. The 9-element modules (sequenced circles in Figure 2) are illustrative as the size of the circles vary, given the priority and cruciality of the issues.

5.1. Crafting a Practical Innovation Pathway for a Carbon-remedied Coal Future

Table 1 summarizes the corresponding linkages of reflective indicators to the pattern co-efficients with respect to carbon capture & usage (CCU), carbon capture & storage (CCS), and carbon-remedied coal future in tandem with CCU and CCS. Bioenergy with CCS is the best-practice case for net negative emissions. The operations chain is burning biomass (e.g., wood pellets) to generate steam for electricity. Then, the CO_2 is captured and buried in the earth subsurface. The Sleipner CCS Project in Norway (1996) has removed almost 17 megatons of CO_2 from the atmosphere. One may draw from the robust regulatory framework already in place for the oil and gas industry. However, there is an urgent need to adapt for storage, usage, and plug-in utilization and incentivize to increase CO_2 storage in both onshore and offshore settings.

Surface and subsurface rights (onshore or offshore) or the leasing of land for CO_2 storage is also essential through policy reforms and to create a sense of well-being by the community. Surface and subsurface rights have significant impact on CCUS projects as CO_2 geological storage projects need to be leased for sustainability. A related dimension is compliance with water, energy, and waste norms of pollution. CO_2 can arise from natural swamps and marshy terrains or be harnessed from gas separation processors and/or chemical or electricity generating plants. However, care about storage is necessary as seepage causes underground water pollution and substrata acidification. CO_2 from natural or processed sources are transited to the allocated site, compressed, and then injected into the conduits of the depleted oil reservoir. Alternating with the CO_2 is water, through a process of water alternating gas, which curbs viscosity of the mixed fluid and improves flow-ability. Indicators and methods for assessing the uncertainties. Scaling the cost barrier would enable CCS with CCU for the future viability of coal-based energy (Wu et al., 2016). Technological innovation of enhanced membrane systems, efficient solvents, and versatile chemical looping processes are key (Bringezu, 2014). Coal undergoes three critical stages: Pre-combustion, post-combustion, and during the oxy fuel (Geerlings and Zevenhoven, 2013). The initial application of CCS technology to large CO_2 emission sources will always require additional incentives to reduce the investment effort, such as payment for avoided emissions. Future research directions necessary for CO_2 capture include (i) improvement of chemical and physical sorbents, (ii) improvement

Figure 2: Pattern coefficient and reflective indicator findings for a carbon-remedied coal future with tandem carbon capture and usage and carbon capture and storage. The 9-element modules (sequenced circles) are illustrative as the size of circles vary based on the priority and importance of the issues



of ion transport and other membranes and integration into power processes, and (iii) elimination of gaps when scaling-up from the laboratory to pilot applications (CSLF, 2010; Baruya, 2017). With respect to CO_2 transport and storage, it is expected less potential reduction costs. Additionally, the effects of impurities in CO_2 transport should be studied, and response procedures should be developed in advance for the possibility of CO_2 pipeline accidents. Safety could be the greatest barrier to CCS implementation (Yang et al., 2019). The public should be convinced that this technology can store CO_2 for long periods with low risk probability for human health and the environment.

6. CONCLUSIONS, FUTURE RESEARCH TRAJECTORY, AND LIMITATIONS

The framework posited herein is expected to benefit several key stakeholders, policy-makers, governance, compliance regulatory promoters, project developers, and beyond. Industrial engineering and management modules, such as adaptive and locally sustainable technology, preventive maintenance, finance–quality–insurance integration, community outreach, and conformity with sustainable development goals have been considered. However, key uncertainties need to be addressed, and the relative importance of variants for technology developers should be assigned, although practice indicates technology variance is dominant. Moreover, authenticity may be improved with availability of storage site data. These steps would have positive buy-in with the society as levels of public awareness would increase, and the community would accept a measurable quantum of risk. Essentially, uncertainty would give way to new opportunities and benefits derived from sustainable usage and storage of captured carbon. In contrast to incremental benefits accruing from mitigation and adaptation measures to curb CO_2, quantum capture may be possible with CCS (NDRC 2013).

The risk of leakage from sites is by far one of the most important criteria that needs to be assessed (EC GD1 2010). Hazards that need critical evaluation encompass three problems: Surface concentration of CO_2, aquifer water contamination, and displacement of fluids forced out by CO_2. CCS epitomizes transformative change with intervention-driven results-based adoption of adaptable, safe, and sustainable CCS technology. Need for change, the readiness of the community to participate, change pathways adaptable to ground-realities, and the ability to imbibe necessary skills and adequate safeguards to sustain transformation are evidenced in CCS. This quantum or transformative change is mandatory to cap the 2° temperature rise globally. Thus, CCS projects befit the scale of change needed. Basically, CCS harnesses the CO_2 emitted from energy producers and industrial processors and permanently stores it, usually by injecting it into underground rock layers. Notwithstanding CCS and CCU, at this emergent stage, is primarily a technological issue, yet spirited dissemination of societal innovation can provide environmental exacerbation solutions.

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