More Than a Pipe Dream: Expanding *SimCCS* Carbon Transportation Pipeline Optimization to Consider Environmental Tradeoffs

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Abstract

Carbon Capture and Storage (CCS) is a pivotal technology for reducing greenhouse gas emissions. While developments have been made in capture and storage capabilities, the planning and development of an optimized transport pipeline network for linking emission sources to storage sites remains understudied. This study aims to extend the capabilities of *SimCCS*, a widely-used CCS planning tool, to incorporate environmental, social, and cultural considerations alongside economic costs of pipeline networks. Utilizing multi-objective optimization, we introduce an additional objective function that minimizes environmental and social impacts. This function integrates spatial data layers representing critical habitats, protected areas, and other socio-ecological factors. Preliminary results illustrate the model's capacity for multi-objective optimization. The annual expense for maintaining a sample pipeline network increased from $434 million to $622 million, with pipeline lengths of 1986 kilometers and 2878 kilometers, respectively, when shifting focus from cost to environmental and social impacts. This research contributes a more comprehensive framework for the planning of future CCS infrastructure that is both economically and environmentally sustainable.

1 Introduction

According to findings from the Intergovernmental Panel on Climate Change [1], reaching a net-zero emissions target by 2050 is crucial for meeting the Paris Agreement goals. Carbon capture and storage is increasingly considered a vital tool for emissions reduction [2], particularly in industries that are difficult to decarbonize [3, 4]. While there have been advances in capturing carbon emissions from various facilities, a significant obstacle lies in creating an infrastructure network that can efficiently connect carbon sources to storage sites [5].

CCS has the potential to play a significant role in meeting the United Nations' Sustainable Development Goals (SDGs) [6]. CCS could also contribute to other SDGs such as affordable and clean energy, industry, innovation, and infrastructure, and responsible consumption and production. However, commercial scale deployment of CCS will involve extensive planning for deployment of large-scale, costly infrastructure projects. Particularly, planning and building large transport pipeline networks present a major obstacle for the practical deployment of CCS [2]. While previous studies in this area have resulted in models that assist in the design of economic cost-optimal networks [7, 8, 9, 10], they do not account for non monetary cost such as ecological damage.

Evidence from other pipelines and linear infrastructure corridors [11, 12], such as roads and oil and gas pipelines, demonstrates short- and long-term ecological impacts. This study incorporates an

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additional objective function to the *SimCCS* model [8], which is used with environmental, social and culturally relevant spatial data to minimize for both private economic and public environmental cost.

2 Literature Review

A metastudy of the existing literature on CCS in 2018 by Viebahn and Chappin [13] revealed a significant imbalance in research focus across the various components of CCS. In the study, papers are grouped into nodes and overlapping clusters of nodes based on topic grouping. The sizes of the nodes dedicated to the topic of transport network optimization range from approximately 20 to 70 papers. In contrast, the areas focusing on capture and storage boast nodes with up to approximately 450 papers. This evident gap in research focus is noteworthy, as a balanced understanding across all components—capture, storage, and transport—is essential for moving from theoretical developments in capture and storage to successful deployment of CCS infrastructure.

Early efforts in CCS were often extensions of existing fields like chemical engineering for capture and petroleum geology for storage, which already had research momentum [14]. The chemical engineering and petroleum geology backgrounds of many of the researchers in CCS are also evident in transport, where a large body of work focuses on pipeline fluid and thermal dynamics [13, 15], and the approximately 5000 miles of transport pipelines currently in the United States that are used for enhanced oil recovery [16]. The application of CCS for climate change mitigation as a separate agenda from enhanced oil recovery has only been recently in consideration, and it presents a different set of challenges for deployment, mainly relating to scaling [2]; a recent DOE report estimates that up to 96000 miles of pipeline may be necessary to meet the 2050 net zero goals [17].

Pipelines are the most mature and often the most cost-effective method of transporting carbon dioxide in the US, and will be the majority of the transport network capacity for deployment of CCS, as rail, truck, and shipping are several times more costly in comparison [17]. The approximate 5,000 miles of existing pipelines in the US largely connect carbon sources to oil fields for enhanced oil recovery, so new pipeline routes will be necessary to connect sources to suitable geological formations for permanent storage [17]. Planning for these new routes will involve an approach that is capable of addressing multi-objective problems by taking into account geographical and geological suitability, regulatory considerations, and socio-ecological impacts.

The existing literature on CCS transport pipeline network decision planning has approached the path optimization problem using mixed integer linear programming (MILP). Previous studies using MILP for path optimization have mainly investigated regional CCS networks in terms of economic cost, such as in Norway [10], Germany [18], the UK [9], Pacific Northwest US [19], Texas [20], China [21, 22], and Korea [23]. However, Han and Lee [23] and Zhang et al. [22] were the only studies to have included environmental impacts in consideration as a factor of network cost. Environmental tradeoff remains understudied as an aspect of pipeline cost.

Research from other types of pipeline infrastructure projects like roads and oil and gas pipelines [11, 12] shows both immediate and lasting environmental consequences. In the short term, construction activities can lead to the death of plants and animals, disrupt ecosystems, and cause pollution [11]. Over the long term, linear structures like pipelines and roads can fragment and isolate habitats, creating "edge effects" that make ecosystems more vulnerable to various threats [12]. Understanding both the immediate and long-term environmental consequences allows for a more comprehensive assessment of the true cost of potential transport networks, beyond just the financial expenditure [24]. This can lead to more sustainable development by preserving biodiversity, ecosystem services, and overall ecosystem health through avoided edge effects. There are also cultural and socioeconomic factors such as historical sites or disadvantaged communities that should be avoided by pipelines.

3 Methodology

SimCCS is the most widely used CCS planning tool and has comprehensive capabilities for accounting for uncertainties as well as multivariate optimization. In short, the objective function of the original *SimCCS* model minimizes the sum of capture cost, pipeline use cost, pipeline build cost, and storage cost subject to various constraints such as flow conservation, infrastructure capacity, and carbon dioxide capture targets [8]. This study continues previous work [24] to expand the *SimCCS* model by implementing an additional objective function that minimizes the environmental impacts caused by the pipeline network. The first objective function Obj_1 to minimize economic cost is described in more detail in the original *SimCCS* paper by Middleton et al. [8]. The second objective function is defined as [24]:

$$\text{Obj}_2 = \min \sum_{m \in M} \sum_{k \in K} \sum_{c \in C} w_m E_{mk} y_{kc} \quad (1)$$

The weight w_m is assigned to each type m of the environmental or social layers. E refers to the environmental layer attribute. In this context, m denotes the specific category of the environmental layer, while c signifies the trend in pipeline capacity. k is an indicator for a prospective pipeline route. The value of E_{mk} can either be 1 or 0. A value of 1 for E_{mk} indicates that the candidate pipeline route k intersects with the m-th type of environmental or social layers. y_{kc} is an decision indicator to denote whether a pipeline k with trend c is constructed. Currently, all such layers have a default weight of $w_m = 1$. This weight can be modified to reflect the significance of specific layers.

The second objective function is weighted with the original cost objective function as follows by a commonly used method described in Cohon [25] to obtain an aggregate objective function:

$$\min Z = \frac{1}{1+\omega}\text{Obj}_1 + \frac{\omega}{1+\omega}\text{Obj}_2 \quad (2)$$

Where ω is the weighting parameter for environmental and social impact. At $\omega = 0$ this is equivalent to minimizing economic cost only, and as ω approaches infinity the aggregate function minimizes environmental and social impact only.

SimCCS utilizes spatial data that depict a variety of factors affecting construction feasibility and cost. These factors are represented as grid layers in the model and include elements like land cover, direction of slope (aspect), population density, federally-owned lands, rail networks, roadways, terrain incline (slope), and waterways [8]. New spatial data layers were developed to represent environmental and social impacts. Each data layer was processed from the source to conform to the reference input raster specification for *SimCCS*, with a 1984 World Geodetic System (WGS84) coordinate system, and resolution of 0.01 decimal degrees. Feature layers are represented as binary value rasters, with 1 representing the presence of the feature and 0 the absence. The feature layers were used with the *CostMAP* [26] module of *SimCCS* to generate the aggregate cost layer to use with Obj_2 in *SimCCS*. The weight of each cell in the cost network is determined by the number of features that are present in that cell.

Environmental and social feature layers processed and used in the construction of the cost network include critical habitat areas for species listed under the Endangered Species Act [27]; national, state, and local parks [28]; areas of critical environmental concern designated by the Bureau of Land Management [29]; protected areas of the United States, separated by the USGS Gap Analysis Project designations; historic and culturally important sites [30]; Census tribal-designated statistical areas [31]; US Forest Service designated roadless areas [32]; and areas with disadvantaged communities [33]; with ongoing development to add additional feature layers. Geospatial processing was implemented in Python using the ArcPy [34] package. Where the feature layers are polygon layers, they converted to raster layers that conform to the reference layer specifications discussed above.

4 Results

Feature layers which have been processed to be compatible with *SimCCS* are summarized below in Table 1 by name, source, cell count, area, and coverage. More work is ongoing to process and create additional layers to add to and test the model across the lower 48 states [35].

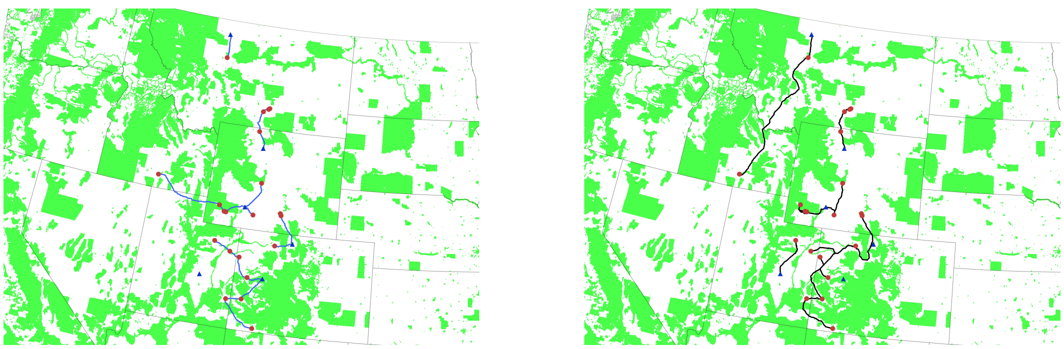
Recent preliminary results incorporate four layers related to environment and society. The four layers encompass critical habitat for species, national, state, and county level parks, historically and culturally important areas, and areas with disadvantaged communities as discussed in the preceding section. Additional environmental layers, including the layers present in the table but not in the results discussed below, will be incorporated as the study progresses.

Two separate scenarios were included in the preliminary result model runs. These scenarios differ based on how much importance is given to reducing environmental and social impacts, with weighting

Table 1: Summary of feature layers

Layer (Source)	**N cells**	**Percent of total cells**	**Area (sqkm)**	**Percent of total area**
Areas of Environmental Concern (BLM)	120415	1.54	121821.59	1.57
National/State/Local Parks (ESRI)	1584252	20.23	1562329.61	20.11
Critical Habitat (FWS)	619515	7.91	597720.69	7.69
GAP Status 1 (PAD)	391742	5.00	386603.32	4.98
GAP Status 2 (PAD)	1208343	15.43	1175315.05	15.13
GAP Status 3 (PAD)	2798482	35.74	2718378.42	34.99
Historic/Cultural Areas (PAD)	27978	0.36	27983.49	0.36
Tribal (US Census)	371502	4.74	359390.27	4.63
Roadless Areas (USFS)	347658	4.44	333044.88	4.29
Disadvantaged Communities (DOE)	1031441	13.17	1027809.64	13.23

parameters set at $\omega = 0$ and $\omega = 100$. For each scenario, we created cost networks through *CostMAP*. Then, we solved for the optimal connections between 21 CO_2 emission sources and 6 CO_2 storage reservoirs situated in Utah, Wyoming, Montana, and Colorado with the modified *SimCCS* model as discussed above. Figure 1 shows the optimal pipeline configurations under the two scenarios: minimizing private construction and operational costs (1a), and including environmental and social impacts (1b).



(a) Optimizing pipeline network to minimize economic costs ($\omega = 0$)

(b) Additionally minimizing environmental and social impacts ($\omega = 100$)

Figure 1: Mapped preliminary results. Red dots are CO_2 sources. Blue triangles are CO_2 sinks. Green areas are environmentally and socially sensitive areas. Blue lines are CO_2 pipelines.

For the cost-focused scenario presented in 1a, the annual expense for maintaining the pipeline network was found to be \$434 million, covering a total length of 1986 kilometers. However, when an objective to reduce environmental and social impacts was incorporated (as in 1b), the annual cost rose to \$622 million, and the pipeline measured 2878 kilometers in length.

5 Conclusions

This study contributes to the existing literature on CCS by incorporating environmental, social, and cultural factors in the planning of transport pipeline networks. The incorporation of these additional layers into a new objective function of the *SimCCS* model allows for a more holistic evaluation of pipeline network costs. Two scenarios were considered, one prioritizing economic costs and another incorporating environmental and social impacts.

The preliminary result demonstrates the trade-offs between economic and environmental objectives with the CO_2 source in Utah. When the focus was solely on minimizing economic costs, the pipeline extended eastward, intersecting with several environmentally and socially sensitive areas. However, when the optimization algorithm was weighted to also consider environmental and social impacts, the pipeline was rerouted to a northern trajectory that largely avoided these sensitive zones.

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