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# Designing Networked Energy Infrastructures with Architectural Flexibility

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**Abstract**

Development of networked energy infrastructures (like gas pipe networks), generally requires a significant amount of capital investment under resources, market and institutional uncertainties. Several independent suppliers and consumers are to be connected into these networks. However, the actual commitment of these parties and the capacities they require from the network can remain uncertain for a long time. This is a challenging task for development co-owners because decisions, such as network architectures, have to be made while uncertainty exists. In order to effectively explore through the design space and identify architecturally flexible designs addressing a view of capacity uncertainty, a simulation framework based on a combination of Monte Carlo simulation and Graph Theory is proposed. It integrates a stochastic capacity demand model and network design heuristic algorithm. The framework will be able to evaluate architectural design options and show that architectural flexibility can significantly improve the value of the infrastructure project by reducing downside risks and benefiting from upside gains compared to the deterministic design approach.



Keywords:networked energy infrastructures, uncertainty,architectural flexibility

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## 1. Introduction

Energy infrastructures (such as gas pipe and electricity networks) form the back bone of modern society as they provide essential utilities and services. However, society is increasingly challenged with dwindling energy reserves for electricity generation and adverse effects from emission of carbon dioxide from energy use. In response to these challenges several new initiatives are being developed to provide alternatives to fossil fuel and reduce harmful emissions. There are, for example, plans to develop pipeline networks that connect biogas farmers and pool their output for use as alternative fuel, and networks for carbon capture and storage (CCS)[1,2].

In most cases, development of these networks involves several independent organizations to be connected into the network. In the exploratory or design phase of these networks, among others, the capacity of the pipe required by each of the suppliers/consumers is a major uncertainty as the flow from each supplier might change over time. The challenge for the developer, then, is to decide who to connect first and how to develop the network taking the uncertainty into account.

In facing design under uncertainty, the common practice in systems engineering is to find an optimal network that satisfies a fixed set of parameters[3,4]. However, an optimized solution is rigid and does not perform well when uncertainty is high[5]. If the future uncertainty turns out to be favorable, the point-optimized solution is rigid to be expanded and modified, which causes a loss of opportunity. On the other hand if the future turns out to be unfavorable, point-optimized solutions cannot easily be reduced in scale, wasting capital. This calls for an approach that designs networks to be easily changed to adapt to uncertain future conditions.

Flexibility in design is a method to recognize and embrace the effects of uncertainty[6]. The basic premise with introducing flexibility into the design of networks is that it provides the developer with "rights but not obligations" to develop in particular ways[6], given the nature of uncertainty. Flexibility provides "options" in the strict technical sense of the word-these are not just alternatives, they are capabilities to react easily in a number of ways that would not be possible unless designers make intentional choices in the design phase. For example, in the case of biogas network development, flexibility can mean sizing pipe capacity to be able to handle extra flow, anticipating connection to future potential new participants, and so forth. The claim is that flexibility enables the developers to gain from upside opportunities and minimize downside risks[6]. More discussion on the conceptual meaning of flexibility and types of flexibilities in networked energy infrastructures is given in section 3.

In this paper, we propose a computer simulation framework that integrates a stochastic capacity demand model and network design heuristic algorithm to explore network design options. The framework generates and evaluates network designs under capacity uncertainty and shows that flexibility can enhance the value of the network(s) by reducing downside risks and benefiting from upside gains compared to the optimal solution approach which is deterministic.

This paper is organized as follows. Section 2 discusses the characteristics of networked energy infrastructures and conceptualizes them as networks with nodes and links. Section 3 discusses flexibility in energy networks. Section 4 proposes a computational simulation framework for exploring flexible design options under capacity demand uncertainty. Section 5 demonstrates the proposed framework by applying it to the development of a hypothetical network infrastructure. Section 6 concludes this paper.

## 2. Characteristics of Networked Energy Infrastructures

Energy infrastructures have a socio-technical nature, i.e. both a physical and social/organizational structure[7]. Physically, they are highly engineered technical artifacts and facilities for the production-conversion/treatment, distribution and supply of essential energy needs of society. The social structure implies the organization and institutions that design, operate and make use of the technical artifacts. In this paper, we focus on the design of the physical structure and, on an abstract level, conceptualize it as a network of links and nodes housing a certain flow that moves through the links and is processed in the nodes. Links and nodes are generic components of the network. The links are like pipes, cables which traditionally are referred as "infrastructure" and the nodes are like production, processing, storage and consumption sites. For example, a gas pipe network begins with gas production plant (node); the produced gas is transported through pipe (link) towards consumers (node) for the purpose of energy (heat and electricity) or for chemical processing.

The following are some common characteristics of energy networks that make the designing and development planning process very challenging.

- *Capital intensive*: the design and development of these networks require substantial amount of capital investment (usually in hundreds of millions or billions of dollars).
- *Evolving internal and external uncertainty*: these networks are being designed, developed and operated in uncertain environment. For example, the capacity required by suppliers/consumers of the network might change over time.
- *Long life time*: lifecycle of these networks (i.e. design, development, operation and abandonment) spans several decades.

These characteristics, among others, create uncertainty for the project developers and make decision making difficult. The practice of traditional engineering design focuses on finding an optimal solution given a deterministic assumption of the future environment in which they will be operated. Deterministic optimization often leads to a rigid network design solution that is appropriate if the future condition is relatively stable. Such point-optimal designs without taking into account uncertainty may cause huge financial losses. In this paper, we propose a flexible design approach to enable networks to be easily changed to adapt to uncertain future conditions, which is discussed in more detail in section 3.

## 3. Flexibility in Networked Energy Infrastructures

In many disciplines, flexibility is intuitively defined as the ability to respond to changes easily. We define flexibility, as the property of the system, endowed by design at initial stage, which gives it the capability to respond to future changes[8]. De Neufville[6] claims with some strong conceptual reasoning and practical case analysis that flexibility can add value over optimization design approaches. The added value could come either from an increase in expected gain, reduction in maximum possible loss, reduction in initial capital expenditure or a combination of those[6].

In general there are two kinds of flexibilities in networked energy infrastructures: architectural and operational[9]. Architectural flexibility is achieved by designs that enable the system to modify configurations or layouts to future uncertainty with relative ease. Operational flexibility is achieved by designs which allow easy modification of operating strategies without major configuration changes. In this paper we focus on architectural flexibility to explore promising design options and show, on a conceptual level, that there is value compared to a deterministic design approach. In the case of networked energy infrastructure, by architectural flexibility we mean it is possible to:

- *Add or delete nodes or connections*: over the life cycle of the infrastructure, nodes or/and connections can be added or abandoned. When such kinds of flexibilities are exercised, the physical configuration of the infrastructure will change.
- *Modify connections among the nodes*: this means changes in the way nodes are connected or different routes for an existing connection. This type of flexibility is referred to as network re-configurability.
- *Modify the designs or properties of nodes or connections*: this flexibility changes the properties of nodes or connections in a network but not its configurations. For example, capacity expansion of links and/or source or sink nodes.

The challenge of exploring and integrating flexibility comes from the large number of possibilities of designing the network and the implementation of flexibility decisions both temporally and specially. The solution to this challenge should enable flexible connectivity within the considered nodes allowing connection and exploitation of nodes (source or sink) which currently doesn't look feasible to consider but in the future become significant to be connected. It is enabled by initial design, such as the ability of the sink node to accommodate possible increase in capacity from other sources or a pipe that can accommodate possible increment in capacity. To facilitate the task of exploring this complex design space and generate promising design options we propose a computational framework based on a combination of Monte Carlo simulation and graph theoretical approach.

## 4. A Computational Framework

To explore flexibility under capacity uncertainty, this paper proposes a computational framework shown in Fig.1. The key elements of this computational framework include: uncertain variable model, simulation model based on heuristic algorithm, decision rules and evaluation of design options. The loop represents Monte Carlo simulation and each run takes one evolutionary path of an uncertain variable and generates alternative design options and their economic evaluation results. A description of the key elements of the computational framework is provided below.

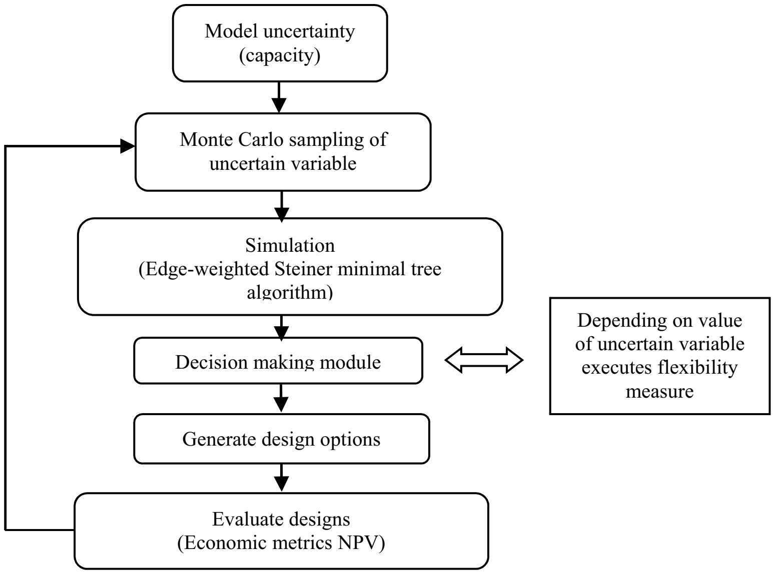


Fig.1. Proposed computational framework to explore flexible design options under capacity uncertainty

- *Modelling capacity demand*: In this research we develop a stochastic capacity demand uncertainty model based on an analytical approach. Capacity required by the participant (node) in the energy infrastructure network can also be otherwise represented by flow from or to that particular node. By making some initial assumptions on flow estimates from nodes (i.e., type of distribution, speed of convergence), this approach avoids requiring large samples of historical data. The first step is to transform an initial flow estimate into a probability distribution, such as, normal distribution characterized by vector D (t0) containing the moments of the distribution (mean and standard deviation). The second step is to generate an ensemble of flow estimate trajectories F (t) given the model, shown in Fig. 2.

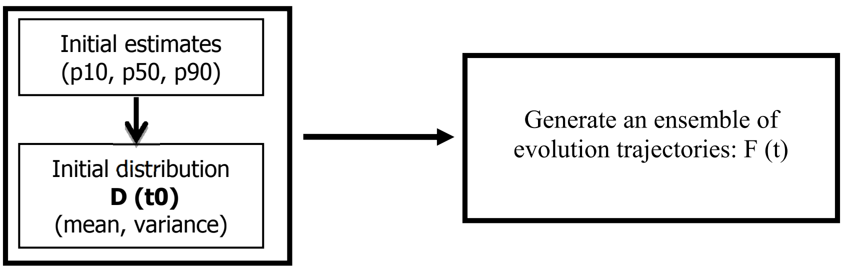


Fig. 2 Model framework for flow uncertainty

- *Simulation model*: this is based on a graph theoretical concept of an edge-weighted Steiner minimal tree, which finds a minimum cost tree-shaped network connecting the nodes. In a graph theoretical representation of networks, the sources of flow are nodes and their connections are edges. The edge-weighted Steiner minimal tree generates the minimal cost connection between the existing nodes taking into account the length and the size of the edges (for example, capacity of pipe in gas network). The cost of building the pipeline $e$ is defined as $C_e = l_e q_e^{\beta}$, as in[10]. Here $l_e$ is the length of $e$ and $q_e$ is the total capacity of pipeline $e$. The exponent $\beta$ is the cost exponent for the capacity with $0 \leq \beta \leq 1$. If $\beta$=0, the capacity of the pipelines has no influence on the costs. If $\beta = 1$, building two pipelines of capacity 1 is just as expensive as building one pipeline of capacity 2. We took $\beta$=0.6 as in[11], indicating that there are cost advantages to building high-capacity pipelines. The total investment cost $C(T)$ of a network $T$ is the sum of all edges costs.

$$C(T) = \sum_{\forall e \in E(T)} l_e q_e^{\beta} \qquad (1)$$

where $E(T)$ is the set of all edges in a network tree $T$.

Depending on the value of the uncertain variable(s), the simulation model generates multiple architectural layouts (network designs). A detailed explanation of how the minimum cost edge-weighted Steiner minimal tree can be found in[11,10].

- *Decision rules*: these are a set of heuristics which set up the condition for exercising flexibilities. In the simulation, the decision rule determines when and how to exercise flexibilities (i.e. add nodes, modify configuration, increase capacity of edges) according to evolution of the flow.
- *Evaluation of design options*: accumulative distribution of the net present value is used as economic output of different design options. It is calculated based a simplified cost and revenue model. The cost model is represented as $eq$ $(1)$. The revenue model calculates the expected income based on the flow from each of the supply sources. It is assumed that the incomes are linear in the used capacity of the network. The expected incomes ($EI$) for a chosen network $N$ are therefore defined as

$$EI(N) = \alpha \sum_{\forall S} q_{T(N)} \qquad (2)$$

where $q_{T(N)}$ is the used capacity from the source/sink in network $N$ and $\alpha$ is a constant coefficient representing, for instance, the service charge per unit capacity used.

## 5. Hypothetical network as case study

This section demonstrates the proposed framework by applying it to the development of a hypothetical pipeline network. The case study explores different flexible design options for the network and compares it against the deterministic design. The hypothetical pipeline network could be a typical energy infrastructure, which transports material X[1] from different supply points (physical sources) to demand point(s) (physical sinks) through the links (such as pipes and compressor stations). We specify that the hypothetical network has visible physical links and nodes as in for example gas pipe networks and CCS networks.

In practice, there are several conditions for development of such network infrastructures. Firstly, the benefit from the source points should be able to justify the capital investment needed in their connection to the demand point (physical sink). Secondly, certain physical constraints like distance (pressure and flow assurance limitations) have to be satisfied. The third is the contractual time constraints for investment recovery between the network developer and the suppliers/consumers. All these may result in delaying the investment decision in the network development until the potential sources/consumers have been completely explored and appraised, contractual issues are addressed and the economic viability is justified.

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□ By material we mean flowing matter in gas or liquid state

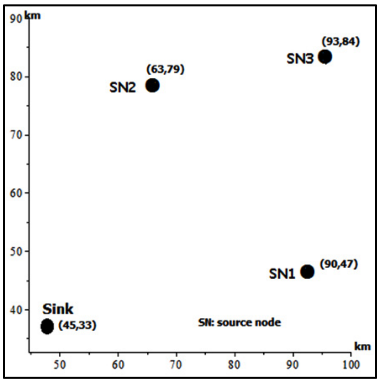


Fig. 3. Layout of a hypothetical network with position coordinates. Black circles represent nodes (source and sink)

We consider a case by which a developer who sees a potential market for X is interested to develop a pipe network connecting suppliers to consumer(s). At the initial stage we assumed the suppliers are interested to sell their X if they have access to pipe network. However, for the developer, the capacity of the pipe required by each of the suppliers is uncertain as the flow from each supplier changes over time. To demonstrate the application of the proposed framework clearly we chose a network that includes three supply points (source nodes) and one sink, see Fig. 3. The situation is hypothetical and the numbers used are stand-ins to permit calculation.

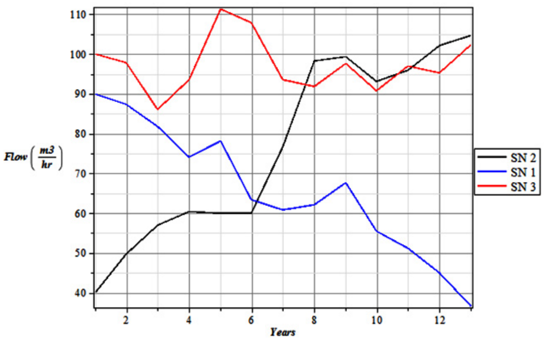


Fig 4. Simulated evolutionary path of flow estimate for hypothetical network

The first task is to model the uncertainty behaviour of flow from each of the suppliers. A normal distribution of initial flow estimate for each source node is defined. The mean of the flows for each of the three source nodes is taken: i.e. SN1= $90m^3/hr$ , SN2= $40m^3/hr$, and SN3= $100m^3/hr$. Then, an ensemble of flow evolution trajectory for each source node is generated for a time period of 12 years, shown in Fig.4. The evolutionary flow path curves represent a situation that exists as problem in practical network design that with time supply from a given source could remain relatively unchanged (SN3), or decrease (SN1), or increase (SN2). It shows that, SN2 has a low flow for the first 6 years but drastically increases in the years after and flow from SN1 decreases continuously over time. The sink node is assumed to absorb any amount of flow coming from the three sources.

If the capacity of the pipe connecting to SN2 is designed based on the flow estimate at the beginning, then there will be an opportunity to be lost and designing the pipe network taking into account the initial flow estimate for SN1 will lead to underutilization of pipe capacity. For the network developer, a decision has to be made taking into account the future opportunities from connecting to SN2 and the potential risk from connecting to SN1. This calls for the developer to adopt a flexible strategy that integrates options at the initial stage to make use of upside opportunities and minimize down side risks.

In practice, stage development that involve core (premising) sources and several potential sources with flexible connectivity becomes an attractive strategy for a project with many low flow sources. In the case of oilfield development the connection to small fields is known as tieback[9]. In this research we use the term ‘flexible connectivity’ for such kinds of connection to potential sources other than core sources. Flexible connectivity allows connection and exploitation of other sources which currently do not look feasible to consider but in the future may become significant. This will change the architecture (topology) of the network. It is enabled by initial design, such as the ability of the sink to accommodate possible increase in capacity from other sources or a pipe that can accommodate possible increment in capacity.

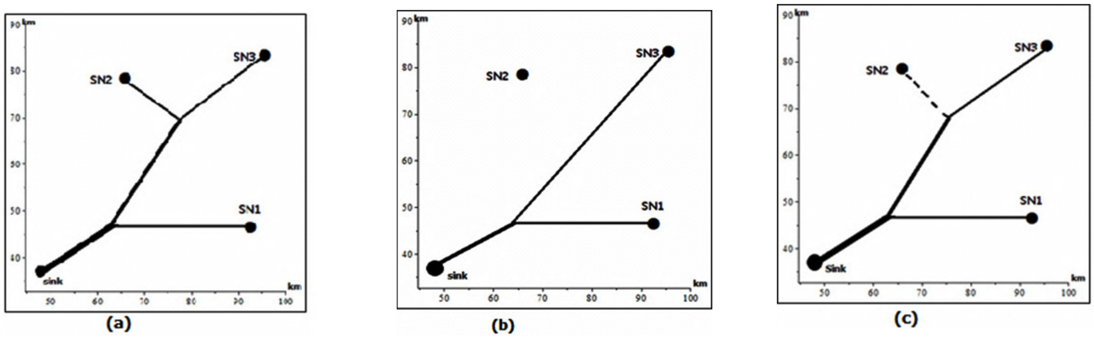


Fig.5. layout of three generic network design strategies

The next step then is to identify and define potential flexible connectivity options and define the triggering conditions governing when we should exercise these flexibilities. Given the trajectory of flow from supply sources (Fig. 4.), three strategies for connecting the networks are identified, shown in Fig.5. (a-c).The first strategy (Fig.5.a) is a deterministic design by which all the supply nodes are connected with capacity based on the distribution of the initial flow estimate (year 1). In this case, only the mean of the flow at initial stage are considered and the capacity of the pipe required by each supply node is fixed. The second strategy (Fig.5.b) is also deterministic by which the decision maker decides to ignore connecting SN 2 because its flow is not significant enough to justify connection just based on year 1 value. The third case (Fig.5.c) is a flexible design connecting nodes which have significant flow at initial stage (SN1 and SN 3) and builds the option of connecting to SN 2, represented in dash line in Fig 6.c. When the flow from SN 2 makes economic benefit the developer will exercise the option (build connection to SN 2). The cost of taking the option in this case is the investment cost of extra pipe capacity and length in design (c) compared to design (b). The option will be exercised when the revenue from SN 2, calculated using equation (2), due to the increase in flow exceeds the cost of its connection. Exercising the option will then change the architecture of the network.

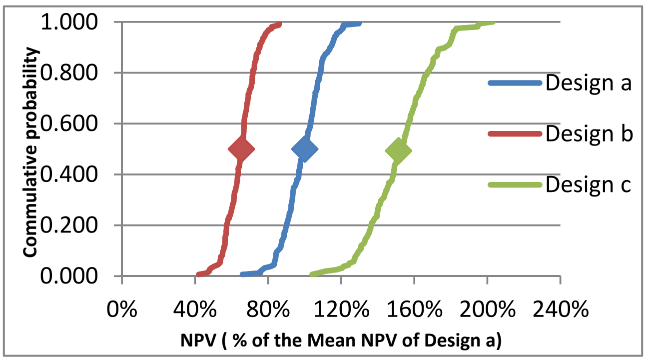


Fig.6. Cumulative probability distribution of NPV

Each of the three design strategies was run through the algorithm shown in Fig.2 for 160 times. Depending on the value of flow from each supply nodes the algorithm provided low cost connections (networks). In each cycle of run, the algorithm also calculated the economic output as net present value (NPV). We then sorted the resulting 160 NPVs calculated for each strategy and plotted them as cumulative distribution function for NPV, shown in Fig.6. To permit comparison between the three designs, we normalize the 160 NPV values for each design against the mean NPV value of design (a).

From Fig.6.we can see that design (c) has higher NPV than the other two deterministic designs. More specifically, the mean NPV of design (c) is 50% higher than the mean NPV of design (b) and 90% higher than mean of design (a). The improvement in expected net present value of design (c) is because of the flexible connectivity, which reduces downside risks and capitalizes on upside opportunities. The downside risks comes from the decrease in flow from SN 1, faced by design (a) and the low initial flow from SN 2 faced by design (b). The opportunities comes from the increase in flow from SN 2, which is missed by design (b) and will not be fully exploited by design (a). From Fig.6.it is also visible that design (a) which connects all source nodes deterministically is better than design (b). This is because the capacity from SN 2 is fully utilized all the time and generates revenue in case of design (a), while both design (a) and (b) are similarly exposed from underutilization of capacity from SN 1.

## 6. Summary and future work

In this paper, we introduced a computational simulation framework which integrates a stochastic capacity demand model and network design heuristic algorithm. The framework is used to evaluate designs and show that architectural flexibility can significantly improve the value of an infrastructure project by reducing downside risks and benefiting from upside gains compared to the deterministic design approach. Applying the methodology to a hypothetical planned network, it was found that the expected net present value of the network development could be raised through the use of flexible connectivity, that build options at initial stages of the design. The framework can also be applied to practical networked energy infrastructures like carbon capture and storage pipe network and gas network.

Further steps in this research entail considering multi-domain uncertainties, such as adding market price of the material flowing through the network and building other flexibility strategies like operational flexibility. Other future works include improving the decision rule and the triggering condition based on practical experience, using empirical data, and performing sensitivity analysis to improve the understanding on the impact of different decision rules on design outcome.

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