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Mapping the Stockholm Vehicle Gas Supply Chain using Network Theory to Assess Local Upgraded Biogas Supply and Demand Relations

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Abstract

The paper uses Stockholm County as a case study to guide our analysis. The region not only concentrates the largest number of inhabitants in Sweden but also holds alone around 35% of the Swedish fleet of passenger cars using gas as fuel. The region's potential vehicle gas demands are 460 GWh by 2020 and 1202 GWh by 2030. The methodological approach relies on Network Theory to guide the numerical analysis of the vehicle gas supply chain in the region. Our results indicates that local vehicle gas supply chain is a rigid structure that might be averse to new entrants such as new distribution companies but, at the same time, it offers opportunities for biogas producers. Distribution companies, especially those placed in the 1st-tier segment are averse to new entrants because they present high homophily and strong ties. Hence, they are more prone to maintain the network's *status quo* since the Swedish vehicle gas market is not yet well developed, which results in a lack of multiple players, which leads to cluster formation.

Keywords: *Biofuels; upgraded biogas; vehicle gas supply chain; network analysis, Stockholm County.*

1. Introduction

Assuming a *Business As Usual* (BAU) growth, the final energy use of vehicle gas in the Stockholm County based on regional statistics between 2007 and 2014 indicates that by the year 2020, the vehicle gas demand ranges between 449 and 471 GWh. For the year 2030, it ranges between 1 036 to 1 368 GWh (Trafikanalys, 2014; Swedish Energy Agency, 2012,2013a, 2013b, 2014; Gustavssom et al., 2011; BiogasÖst, 2014; Sköldberg et al., 2010). These estimates are very conservative when compared with figures from the *Baltic BiogasBus* project, which is a cooperation program between the European Union and the Baltic region to stimulate the use of upgraded biogas as fuel for city buses. Their report assumes a vehicle gas demand for Stockholm County of around 800 GWh already in 2020 (Jonerholm, 2012). For the purpose of this analysis, we opted to continue with our conservative assessment and adopt the respective mean values for the years 2020 and 2030. Hence, the future demand of vehicle gas in the region would account for about 460 GWh by 2020 and 1 202 GWh by 2030.

Our study relies on secondary data collected from governmental institutions and statistical database. Academic publications and reports from important stakeholders are used to complement and validate processed information. Primary data has been acquired through interviews and personal communications with company staff, municipality representatives, and governmental analysts. Network Theory creates the foundation of the methodological steps. This theory concerns with the study of interrelations between discrete objects, such as organizations (Wasserman et al., 1994; Jackson, 2008, Newman, 2010). In our case these objects are defined by the vehicle gas supply chain and the methodological steps include (i) mapping of the network so as to produce numerical data, and (ii) identification and quantification of centrality measures of the local vehicle gas supply chain using *Gephi*, which is an interactive visualization and exploration platform for complex systems and dynamic networks (Bastian M et al., 2009).

2. Numerical analysis of the Stockholm vehicle gas network

Let the network (N, g) indicates the vehicle gas supply chain within Stockholm County. In which a set of nodes $N=\{1,\ldots,n\}$ refers to local stakeholders (i.e. companies or organizations) and their physical structures (i.e. filling stations or production plants) and a real-valued $n \times n$ matrix g, where g_{ij} represents interrelations between these stakeholders using values of 0 or 1. The idea is that two stakeholders or their physical structures are either connected or they are not. If $g_{ij}=1$ then i is linked to j, otherwise $g_{ij}=0$. Note that self-connections do not have impact in our case study, therefore, our model adopts $g_{ii}=0$ for all i.

Our study nominated 45 nodes to represent local stakeholders and their physical structures. These nodes were divided into eight categories so as to represent the vehicle gas network in the region. These categories are: *S nodes* – organizations owning biogas production plants (3 nodes); *P nodes* – biogas production plants (4 nodes); *U nodes* – organizations managing upgraded biogas production (3 nodes); *I node* – natural gas imports (1 node); *D nodes* – organizations distributing vehicle gas (3 nodes); *B nodes* – organizations operating filling stations (6 nodes); *F nodes* – filling stations offering vehicle gas (22 nodes); and *C nodes* – vehicle gas demands (3 nodes).

Networks can be defined as directed or undirected and connected or unconnected; our analysis describes the vehicle gas network within Stockholm County as an undirected and connected network. It is undirected for the reason that supply chains are reciprocal relationships, in which there is a bidirectional exchange of products, services, finances, and/or information between nodes. For example, a trading relationship within a given supply chain means that both partners need to agree to it, therefore, $g_{ij}=g_{ji}$. The local vehicle gas network is also connected because every two nodes in the network are linked forming a single network component (Jackson, 2008). Our study identified 81 links representing direct relationships among nodes that establish the network for the year 2013.

An important aspect of Network Theory is the fact that networked relationships are based not only on direct relationships among nodes but also on nodes being impacted by indirect relationships. Hence, analyzing a path among nodes can capture these indirect relationships. For example, companies that are already connected through business relationship might offer benefits to each other over a non-business partner within the same network, which can indirectly suffer from their relationship. A path in the vehicle gas network consists of a set of involved nodes and a set of links between these nodes. Meaning, it is a sequence of links $i_1i_2, i_2i_3, \ldots, i_{(k-1)}i_k$ such that $i_ki_{(k+1)} \in g$ for each $k\in\{1,\ldots,k-1\}$, with $i_1=i$ and $i_k=j$, and such that each node in the sequence $i_1, \ldots, i_k$ is distinct (Jackson, 2008).

The next analytical step was to translate these data into a graph so as to enable visualization of relationships within the vehicle gas supply chain. Network graphs are generated using mainly "force-based" algorithms in which linked nodes attract each other and non-linked nodes are pushed apart (Hu Y., 2006). Different algorithms present different topologies and they highlight different characteristics of a given network. Since our analysis is framed using the supply chain structure, we applied a graph topology that highlights complementarities among nodes to emulate the topology better representing the vehicle gas network within Stockholm County. We opted for the Yifan Hu graph drawing algorithm for mapping the vehicle gas network within Stockholm County because it combines two algorithms, force-directed and multilevel, to reduce complexity and increase graph readability (see **Fig.1**). Note that each node within the network has its size based on the amount of energy that it manages or consumes. For example, the node C3 represents the overall vehicle fuel demand in the region for the year 2013 and its size matches 412 GWh that is the amount of energy consumed in that same year. Link thicknesses also indicate the amount of energy that flows between two nodes. The graph displays nodes with high degree in its center. Degree of a node is simply the number of links that a node has. For an undirected network the degree of node i in a network g is denoted as $d_i = \#\{j: g_{ij}=1\} = \#N_i(g)$.

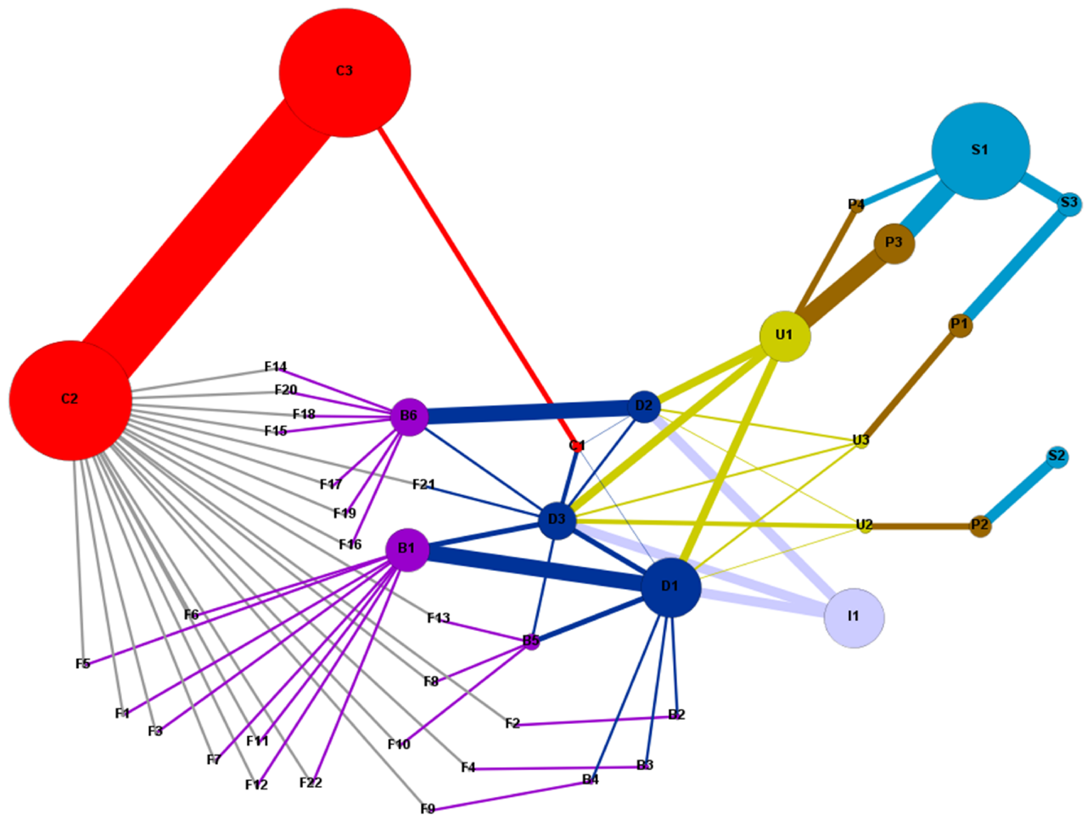

Fig. 1. The vehicle gas network within Stockholm County based on Yifan Hu graph drawing algorithm.

The graph also allows us to use numerical analysis in order to describe network relationships and highlight key structures (Jackson, 2008). For example, degree distribution captures a small amount of information. Yet, it gives important hints into network structure.

The degree distribution of the local vehicle gas network, which is plotted in **Fig.2**, shows that around 76% of nodes have relatively smaller degrees than the average degree of about 4. The large degree nodes concentrate and/or irradiate the majority of flows (i.e. information, financial, or energy flows) within the network; therefore, they are defined as hubs. In principal, hubs can be both strength and weakness of a network depending on their numbers. If failures occur at random within a given network with a great number of small degree nodes, it is very unlikely that a hub would be affected. Also, the existence of more hubs can safeguard network stability if one of the hubs fails (Jackson, 2008).

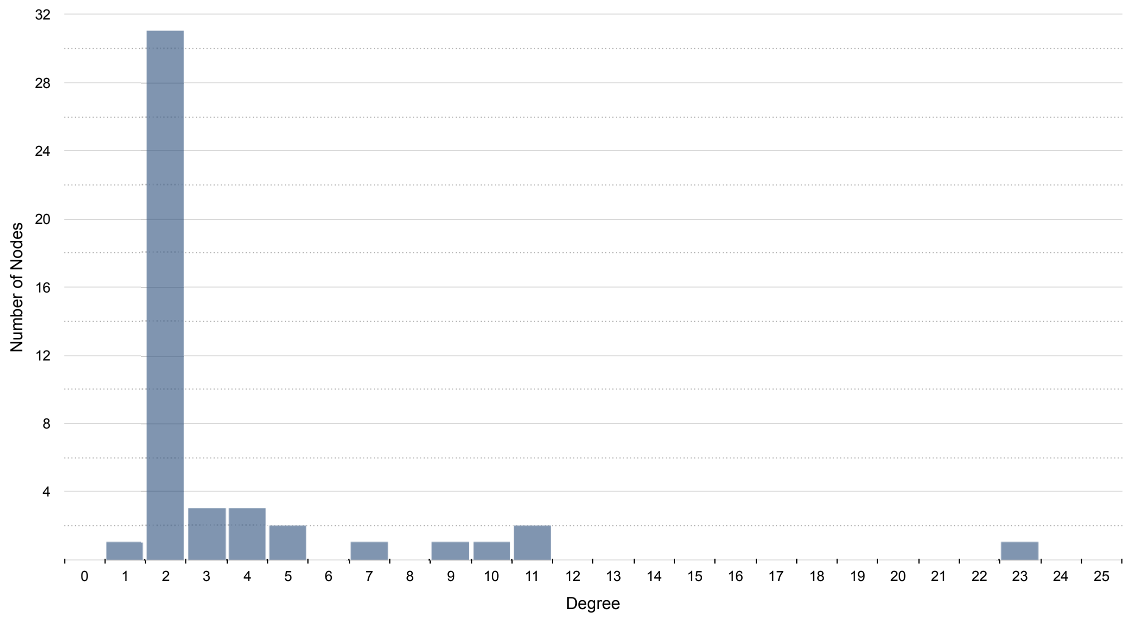

Fig. 2. Degree distribution of the vehicle gas network within Stockholm County.

Naturally, one of the hubs that we easily identified in the degree distribution is the node C2 representing the gas fleet of passenger cars in the region with degree of 23. The node presents the largest degree because it concentrates the majority of flows supplying the local demand for vehicle gas. However, we identified two other important hubs, both with degree of 11. One is AGA Gas AB (node D1), which upholds the leading position on the local vehicle gas market with the largest share of the market based on commercialized volumes of vehicle gas in the region. Interestingly, the other hub is Stockholm Gas AB (node D3) regardless of the fact that it holds the smallest market share. Note that being identified as a hub indicates that these two organizations have a strong influence onto the local vehicle gas supply chain since they are not only responsible for concentrating the majority of the supply and irradiating them into the network to fulfill local demand but also they are accountable for managing the information flow within the local supply chain.

Another numerical analysis that can be used to describe network relationships is graph density. Density ranges from 0 to 1, where 1 represents a very dense network in which every single node within it is linked to almost all other nodes in the same network. Meaning, the degree of each node is close to the overall number of existing nodes. To measure density, we calculate the total number of existing links in the network divided by the total number of possible links in the same network. Despite being a connected network, the vehicle gas network within Stockholm County presents a low density of 0.082. Meaning, it can be described as sparsely connected network because it is connected by a large number of small degree nodes. In general, sparse networks tend to be rigid structures that avoid or hinder the creation of new links.

Thus far, most of the numerical results described broad characteristics of the local vehicle gas network. In order to identify key players and their potential impacts, our analysis conducted centrality measures that compare nodes so as to understand how a particular node relates to the overall network (Jackson, 2008). There are four different measures of centrality: degree centrality, closeness centrality, betweenness centrality, and eigenvector centrality.

3. Results: key players and their potential impacts

Degree centrality shows how connected a node is and how many other nodes can this particular node reach directly and indirectly. For example, degree centrality can provide an insight about collaboration and partnerships within the local network. **Fig. 3** shows the graph with the distribution of results for the vehicle gas network within Stockholm County.

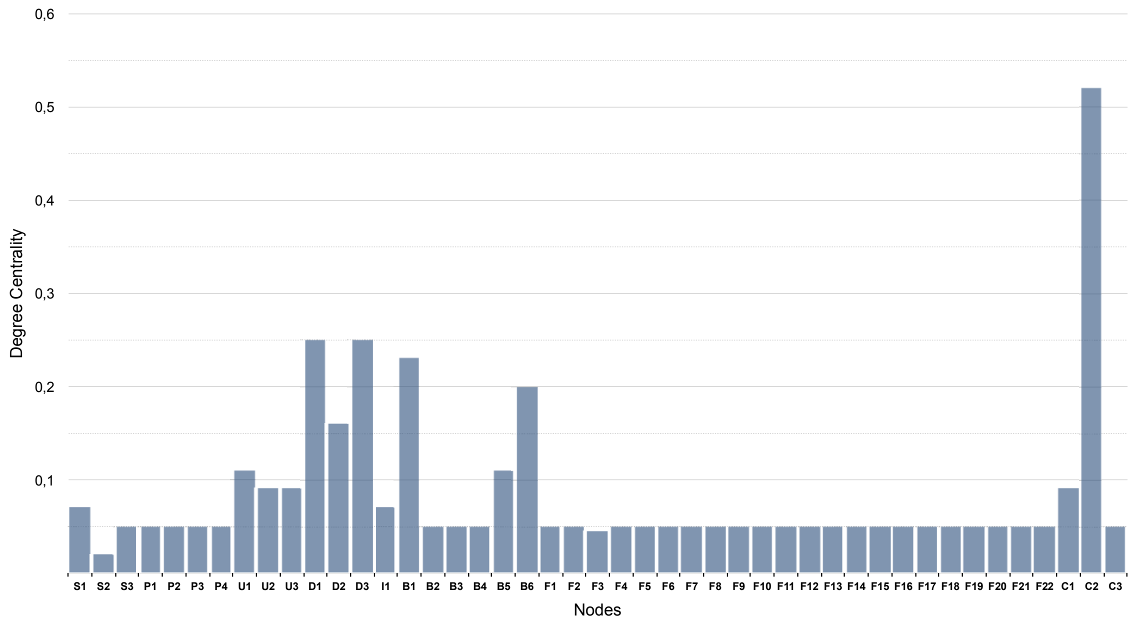

Fig. 3. Degree centrality of the vehicle gas network within Stockholm County.

Our results ratify that AGA Gas AB (node D1) and Stockholm Gas AB (node D3) orchestrate current collaboration within the local supply chain so as to meet the growing vehicle gas demand of passenger cars (node C2).

Closeness centrality displays how easily or fast a node can reach other nodes in the network. For example, closeness centrality can provide an insight about how fast a particular impact from a particular node will spread to the rest of the network. **Fig. 4** presents the graph with the closeness centrality distribution for the vehicle gas network within Stockholm County.

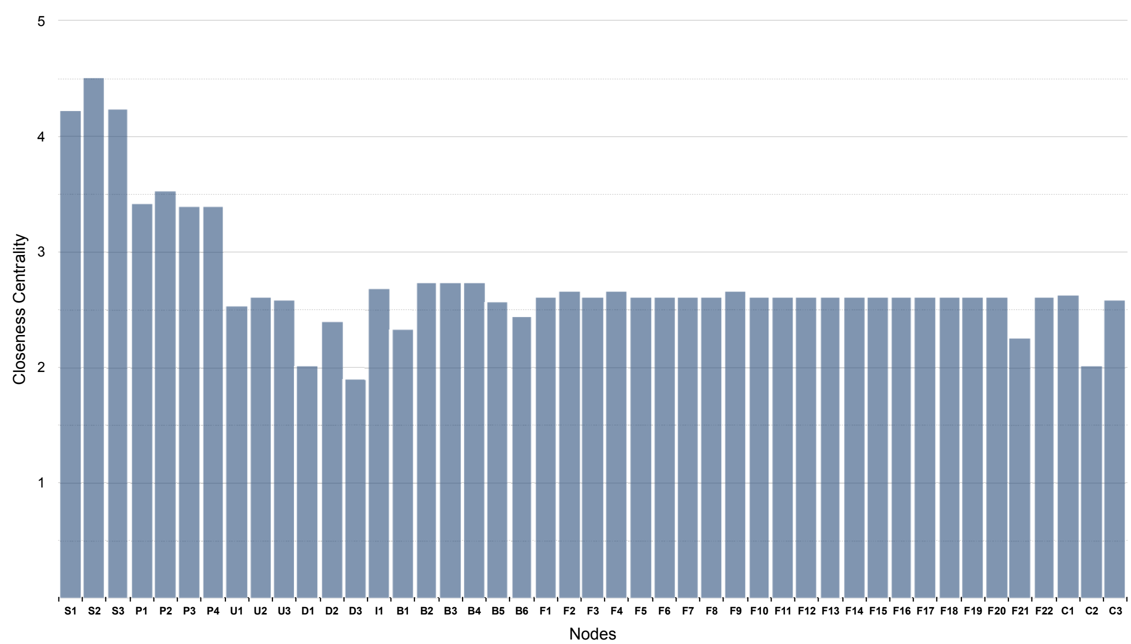

Fig. 4. Closeness centrality for the vehicle gas network within Stockholm County.

Fig. 4 shows node S2 (Käppalaförbundet), which has the highest value for closeness centrality, and the results corroborate the fact that the local vehicle gas supply chain, especially SL's bus fleet (node C1), strongly relies on local biogas production. In order to safeguard its bus fleet against fuel shortage, SL has long-term contract with Käppalaförbundet guaranteeing a monthly volume of upgraded biogas (Wallin, 2014). Hence, any oscillation on local biogas supply, particularly that managed by Käppalaförbundet, can have a strong impact on the region's ability to meet the vehicle gas demand without relying on natural gas imports (node I1).

Betweenness centrality shows how important a node is in terms of connecting other nodes. It measures how likely a given node is the most direct route between two other nodes in the network. For example, betweenness displays which is the most likely node that will be distributing vehicle gas in the region. **Fig. 5** presents the graph with the betweenness centrality values for the vehicle gas network within Stockholm County.

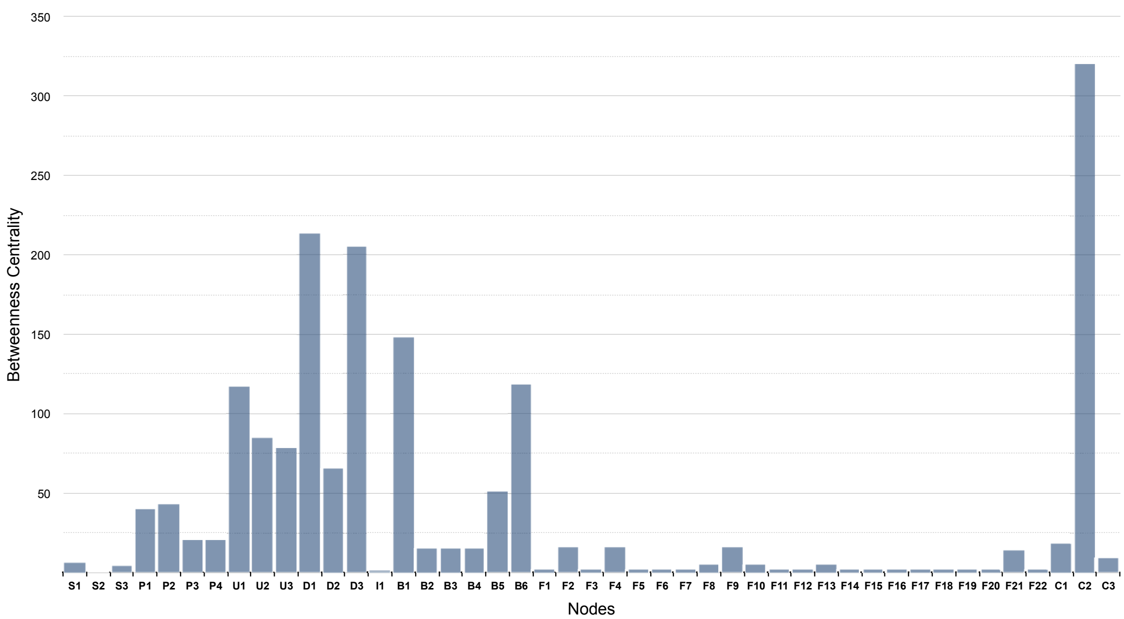

Fig. 5. Betweenness centrality of the vehicle gas network within Stockholm County.

The results displayed in the graph ratify AGA Gas AB (node D1) as the leading organization in the region. An obvious outcome since AGA covers alone around 59% of the local market. However, it was interesting to find out that Stockholm Gas AB (node D3), which holds simply 9% of the local market, is an important node as well. In fact, the results reveal its role on supplying the region with vehicle gas. Another interesting aspect is that natural gas imports (node I1) show fairly low coefficients of betweenness centralities, which could suggest its role as a backup fuel against fuel shortage in the region. The betweenness centrality results also corroborate AGA Gas AB and Stockholm Gas AB as network hubs (see **Fig. 2**).

Eigenvector centrality shows how influential a node is. It measures how a well-connected node impacts other well-connected nodes in the network. For example, it can give insights about which are the key stakeholders within the vehicle gas supply chain in the region. This measure is based on the principle that a node's importance is defined by how important its neighboring nodes are. As a result, eigenvector centrality not only accounts for the connectivity or closeness of a given node but also for its proximity to other influential nodes (Jackson, 2008). **Fig. 6** presents the graph with the eigenvector centrality distribution based on 10^6 iterations in order to reduce variance.

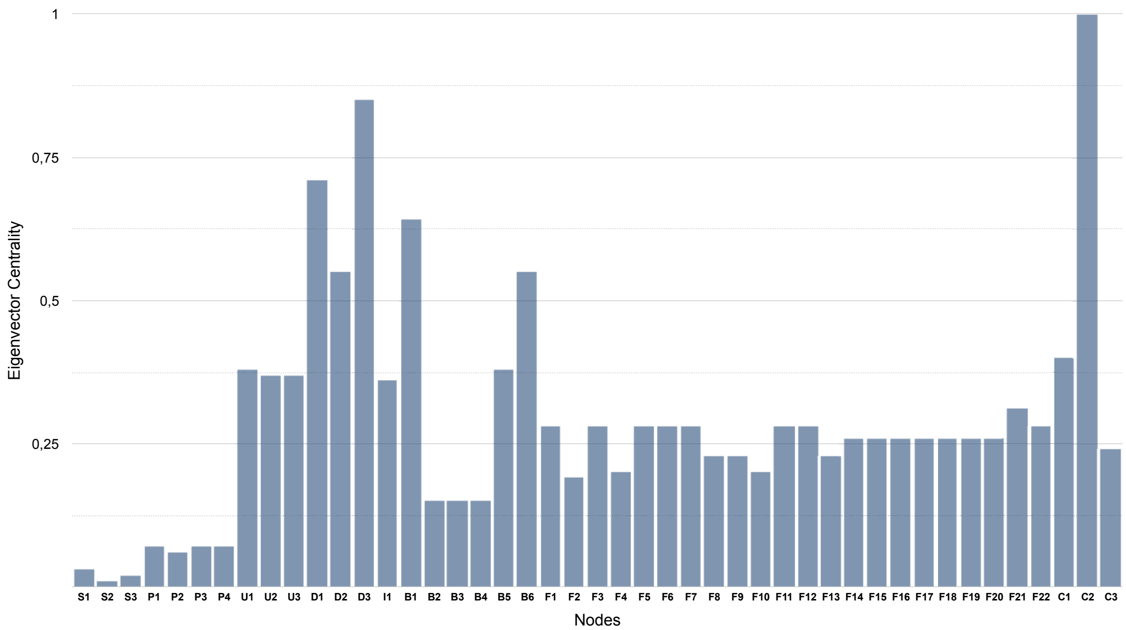

Fig.6 Eigenvector centrality of the vehicle gas network within Stockholm County based on 10^6 iterations.

The results display that nowadays the local vehicle gas network is planned mainly to meet the growing vehicle gas demand of passenger cars (node C2). The graph also shows Stockholm Gas AB (node D3) as the most influential organization in the local supply chain, especially in connection to inter-tiers communication and fuel price stability in the region. This result is further confirmed by conducting an Ego Network Analysis, which measures the degree of separation among nodes. Ego is the way we describe a focal node; therefore, a network has as many egos as it has nodes. Our analysis shows that AGA Gas AB (node D1) and Stockholm Gas AB (node D3) present the largest ego networks. At the 1st degree of separation, both nodes present the same values and they are directly linked to 28% of the network. At the 2nd degree, AGA Gas AB is indirectly connected to 76% of the network and Stockholm Gas AB to 87%, which confirms its influential role within the local vehicle gas network. At the 3rd degree, both nodes are directly and/or indirectly influencing the entire network.

4. Concluding remarks

The Network Analysis indicates that local vehicle gas supply chain is a rigid structure that might be averse to new entrants such as new distribution companies but, at the same time, it offers opportunities for biogas producers. Distribution companies, especially those placed in the 1st-tier segment and represented by D-nodes, are averse to new entrants because they present high homophily (i.e. the tendency of nodes to associate and bond with similar others) and strong ties. Hence, they are more prone to maintain the network's *status quo*. One possible explanation for this is the fact that the Swedish vehicle gas market is not yet well developed, which results in a lack of multiple players, thus, leading to cluster formation. The analysis has also shown that two major hubs, AGA Gas AB (node D1) and Stockholm Gas AB (node D3), present strong ties, therefore, being potential key players – particularly node D3 – in the network regarding the role of natural gas in the region.

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