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Sustainable Energy Transition for Cities Based on Long-Term Planning Supported by a Fuzzy Cognitive Map

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ABSTRACT

The present study was aims to explore resilience and transformation capabilities and explore their applicability in the field of energy. It focuses especially on the role of the cognitions of stakeholders and decision-makers in the uptake and management of sustainability transitions. Fuzzy cognitive mapping (FCM) is used to aggregate different stakeholders' views on the functioning and performance of the urban energy system of the city of Tehran. In the case of Tehran, the urban energy network is analyzed in terms of resilience and transformability by studying the degree of connectivity and its influence on both system characteristics. Three scenarios of policy options are simulated to weight their outcomes in terms of sustainability, Scenario A: Optimization of economic incentives; Scenario B: Strong education and awareness campaigns; and Scenario C: Stronger local institutional initiatives. Scenario A shows a potential perverse effect if the current economic structure is maintained, even if the economic crisis is overcome. Combining Scenarios B and C provides the best results in terms of sustainability. This suggests that successful transformation in cities should pivot on a combination of top-down and bottom-up actions to unlock resilient but unsustainable states, and that special care needs to be taken when managing highly connected and/or influential elements of the system, as contextual dependencies might hinder the agency of change, particularly in the context of cities. Network characteristics, such as connectivity, can be useful indicators to inform resilience and transformation management, although the double-edge sword nature of connectivity should be noted.

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INTRODUCTION

The idea of urban low-carbon transitions is for cities to move toward a new, decarbonized socio-economic system (Wang et al., 2023). Urban energy transition experiences have built up in the form of individual actions and through collective actions in networks and ambitious targets have been set for low or even zero-carbon (carbon neutral) emissions (Aba et al., 2023). Yet, in practice, concerns about the role of cities in energy transitions relate mostly to the means and resources that cities might have to achieve their carbon objectives in the form of organization, knowledge, technology and action (Akrofi & Okitasari, 2022; Nabi Bidhendi et al., 2021).

Such urban low-carbon transition experiments form part of the global sustainability transition approach to climate change, but the role of cities in global sustainability transitions is far from straightforward (Stermieri et al., 2023). On the one hand, the lack of local capability to directly

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impact on energy policy or transport planning is usually considered as a barrier to developing local transition pathways. In this case, cities may be seen as passive actors in sustainability transitions rather than niches of change (Ivanova et al., 2022; Poon et al., 2020). On the other hand, it is often argued that the role of cities as hubs of innovation, development and knowledge enables them to turn crises into opportunities (Zhang et al., 2023). The emerging literature on resilience, transformability and urban sustainability tends to agree that there is a unique opportunity for cities to become laboratories of innovation and experimental action given their exceptional capacity to kick-start actions on the ground linking scientific knowledge and community participation (Alola et al., 2023; Daryabeigi Zand et al., 2018; Wen et al., 2022).

Concerned by this situation, there is a growing literature that explores the physical and technological capacities of cities to improve energy systems and energy governance while mitigating and adapting to climate change. For example, on the technology side, many studies have helped to further understanding of the potential of solar energy in the urban context (Akrofi & Okitasari, 2022; Forbes et al., 2022; Poon et al., 2020). Others have focused on advancing knowledge of other alternatives for energy efficiency measures and technologies (Alola et al., 2023; Htwe et al., 2021; Ivanova et al., 2022; Katris & Turner, 2021). Some studies focus on the role of green infrastructures (Wang et al., 2023; Wen et al., 2022) or in general on the implication that energy transitions may have for urban planning in the context of achieving more efficient, renewable, more social energy networks (Aba et al., 2023; Mirzania et al., 2023; Stermieri et al., 2023).

Because of the many different interests listed above, it is essential to understand stakeholders' perceptions and cognitions in order to identify barriers to and opportunities for transformation (Katris & Turner, 2021). The way in which actors' cognitions in the form of heuristics, biases and previous experiences affect decision-making processes, including those related to the environment and the relationship between human beings and nature, has been discussed in the relevant literature (Forbes et al., 2022; Mirzania et al., 2023). Adding a cognitive dimension to transition research can help to better inform processes of adaptation and transformation in practice, particularly through participatory methodologies which integrate different perceptions and multiple scales (Kokkinos et al., 2020).

The fuzzy cognitive map (FCM) approach is generally used to represent the behavior of complex systems through causal reasoning (Alipour et al., 2019). It is considered a useful tool for setting management objectives, communicating and learning, especially in the context of scenario planning applications driven by high uncertainty and complexity (Gan et al., 2023). An FCM integrates accumulated experience on the operation of a complex system. It is the result of the aggregation of the knowledge obtained from experts who have their own understanding about how the system operates and how it behaves under different circumstances (Bakhtavar et al., 2021). FCMs are ideal tools for theory development, hypothesis formation, and data evaluation. Their main advantages include the potential to include multiple perspectives and a high level of integration (Poomagal et al., 2021).

The application of FCM in the field of environmental science and decision-making is quite recent. For example, FCM has recently been applied in different fields associated with spatial analysis (White et al., 2021), forest management (Eriksson et al., 2023), energy and markets (Xia et al., 2023) and economics (Papageorgiou et al., 2020). Lastly, it is interesting to note that FCM has also been used in climate change research. The impacts of climate change as perceived by stakeholders in Thessaly, Greece have been studied recently by Kokkinos et al. (2020) with the purpose of developing adaptation options, while Satama & glesias (2020) have assessed the vulnerability of different types of livelihoods. Resilience management is a promising application of FCM as it has the potential to model the non-linear dynamics of socio-ecological systems which are emphasized in resilience approaches (Blacketer et al., 2021). However, the use of FCM for urban decision-making has not yet been sufficiently explored, despite the fact that urban systems and their governance have all the necessary ingredients of complexity (Frank et al., 2017) that make the application of FCM particularly interesting.

To sum up then, the present study sets out to study the inner mechanics of complex urban systems and explores urban climate and environmental governance from the perspective of resilience and transformation in a context of sustainable urban development. The objective of the present study was to (i) exploring sustainability and resilience links; (ii) addressing urban complexity; and (iii) exploring the cognitive dimension. To achieve this specific aims, new approaches from a conceptual and empirical point of view were explored that may help to frame adaptive and transformative processes; can address and manage both natural and human capital; can better represent interconnections, systemic complexities and unsustainable lock-ins; and can take into account the perceptions, values and understanding of the actors involved in the system as enablers or with holders of processes of transformative change.

MATERIALS AND METHODS

Fuzzy cognitive mapping

FCMs consist of concept nodes (C_i) that can be interpreted as variables. These concepts are related through direct edge or arcs ($C_i C_j$) that are signed and weighted (w_{ij}) and can be graphically visualized. The weight assigned [-1;+1] represents how strongly concept C_i influences C_j, and the positive or negative sign indicates whether the relationship is direct (+) or inverse (-). The state vector $A=(A_1, A_2... A_n)$, represents the state values of the FCM concepts, A_i [0;1], at the initial stage or after several iterations. Lastly, the adjacency matrix, E, represents the weights of the edges (w_{ij}) (Martinez et al., 2018; Papada et al., 2019).

The dynamics of the state vector A are calculated by focusing on the influence of each factor on the others over a number of iterations, or time steps (k), normally, 20-30 iterations. This is represented by Eq. 1 (Kosko, 1896).

$$A_i^{(k+1)} = f\left(A_i^{(k)} + \sum_{\substack{j\neq i\\ j=i}}^{N} A_j^{(k)} W_{ji}\right) \quad (1)$$

where $A_i^{(k+1)}$ is the value of concept C_i at time step k+1; $A_i^{(k)}$ is the value of concept C_i at time step k; $A_j^{(k)}$ is the value of concept C_j at time step k; and w_{ij} is the weight on the influence from C_i to C_j.

Eq. 1 is used to analyze the dynamic behavior of the network and enable scenarios to be built up upon the establishment of certain fixed conditions (defined here as alternative transition pathways). The state vector A of the baseline scenario is calculated by initially setting the state values of all the concepts in the network to one. Different scenarios can then be modelled.

The network characteristics can also be analyzed through indicators such as density (D), centrality (Ct), out-degree (Od) and in-degree (Id). D is an indicator of the general connectivity of the network, estimated by dividing the number of existing connections by the total number of possible connections between all the variables (N) (Kosko, 1896). It is often assumed that a higher value for D indicates more possibilities of change (Pereira et al., 2020), as there are more connections in the network which, if perceived by the stakeholders, these can turn into catalysts of change. Id, measures the weight of all connections going into a particular node. It demonstrates how much that node is influenced by others (Kyriakarakos et al., 2017). From earlier definitions, a transmitter would have an indegree of zero as other nodes do not influence it. Id is calculated by Eq. 2 (Kosko, 1896).

$$Id = \sum_{j=1}^{N} |W_{ji}| \quad (2)$$

where the node under consideration is C_i, N represents the number of nodes connected to node C_i and w_{ji} is the weight of the connection entering node C_i from node C_j. As Id is calculated for each node individually, this falls in the node metric category. Strong Id indicates that the node is heavily influenced by one or multiple other nodes.

Od, measures the weight of the connections going out of a particular node demonstrating how much that node influences others. As such, a receiver would have an Od of 0 as it does not influence other nodes (Çoban et al., 2017). This metric is the exact opposite of Id and is also a node metric. The equation to calculate the Od of node is as follows (Kosko, 1896):

$$Od = \sum_{j=1}^{N} |W_{ji}| \quad (3)$$

where w_{ij} is the weight of the connection going from node C_i to node C_j. Stronger Od indicates that the node heavily influences the whole map or a particular node.

Ct denotes the importance of each concept. It is also used as a measure of the specific connectivity of each concept. Here, Ct is calculated as the sum of a concept's Ids and Ods as presented in Eq. 4 (Kosko, 1896).

$$Ct = Id + Od \quad (4)$$

where, Id is a measure of the strength of the influence of other concepts on C_i regardless of the sign of the arcs and Od is a measure of the strength of the influence of one concept C_i on others, regardless of the sign of the arcs.

Eq. 1 is used in the case study to generate scenarios. Eqs. 2-4 are used in the network analysis of the case study.

Data collection in the case study

In this case study, 14 stakeholders (hereafter called experts) were requested to develop an FCM for the use of energy in the city of Tehran. This was done through a face-to-face interaction. The experts that took part in the study came from a variety of backgrounds and included people from the civil administration, non-governmental organizations (NGOs), representatives of the general public, academics and private companies with diverse technical backgrounds, e.g., law, planning, sustainability, social behavior, building, energy infrastructures and management. The key engaging topic/question (Q) used to stimulate participants was: "What do you think influences the use of energy in Tehran and what are its impacts?"

As these experts were interviewed, individual maps containing the concept elements (C_i), their interconnections (C_i C_j) and also the weights of those relationships (w_{ij}) which are inputs to the adjacency matrix E were obtained. To that end, each stakeholder followed a specific step-process to create their individual map. First, they listed the elements that might have a role concerning the topic Q and placed the main element in the middle of a blank sheet of paper. Then, they placed the rest of the elements around the first one, making the appropriate connections and indicating whether the relationship was positive or negative. Finally, they weighted each relationship on a scale [0;1] (0 meaning no causal relationship).

FCMapper software was used in this study, based on worksheets in visual basic for application (VBA) coding. To aggregate the individual maps, the weights of the connections were added up and then the entire matrix was normalized. For this process of aggregation, each map is first translated into a matrix and then, after a process of merging similar concepts and renaming ambiguous ones, the maps are aggregated into a single composite matrix. In this case the exercise resulted in a matrix of 86 merged concepts from a total of 139 in the original phase.

RESULTS AND DISCUSSION

Network analysis in the context of resilience and transformability

Aggregating the individual maps collected in stakeholders' interviews resulted in a network (Figure 1) that comprises 86 concepts, hereafter referred to as variables, and 161 linear connections. The variables are organized into nine groups according to thematic issues: (1) Environment & resources; (2) Innovation & opportunities; (3) Social behavior; (4) Local competences; (5) Economy; (6) Lifestyle; (7) Governance; (8) The energy business (i.e., the corporate energy sector); and (9) Supply & demand. The network is represented as a visual map in Figure 1, which shows the urban energy network as seen by a group of stakeholders with interests in energy management, production, supply and consumption in the city of Tehran.

The network has a D index of 0.022. This means that 2.2% of the maximum number of connections that could potentially exist in theory between the 86 concepts (D_{max}=1) are actually made. Unless this value is compared to another network representing a similar topic (energy transition towards sustainable low-carbon environment in Kokkinos et al., 2020), there is no way of knowing whether this is a low or high level of connectivity in an urban energy context. In general terms, given that the aim is to stimulate transformations towards a low carbon system, it is assumed that a high D is desirable (Nikas et al., 2020). But of course, having the seeds to stimulate a change does not mean that the change will lead to desirable impacts. Controlling the agency of change or transformation is critical if the aim is to generate more sustainable and resilient urban energy systems (Klemm & Wiese, 2022).

Figure 2 compares the different levels of the indicators Ct, Od and Id for those with a significant Ct value. For the sake of comparison, Figure 2 only shows the indices relative to the maximum Ct i.e., Ct max 13.25 observed in Energy price (households), which means that

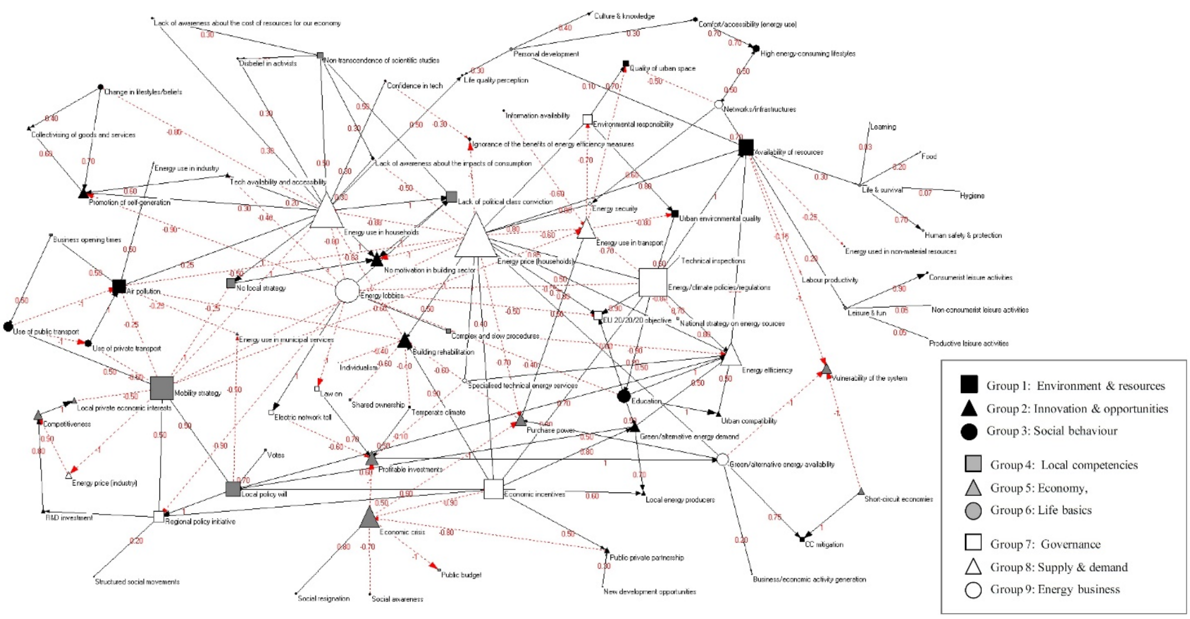

Fig. 1. The cognitive urban energy map of Tehran in graphic form. Negative connections (negative w_{ij}) are represented by dotted lines. Positive connections (positive w_{ij}) are represented by solid lines

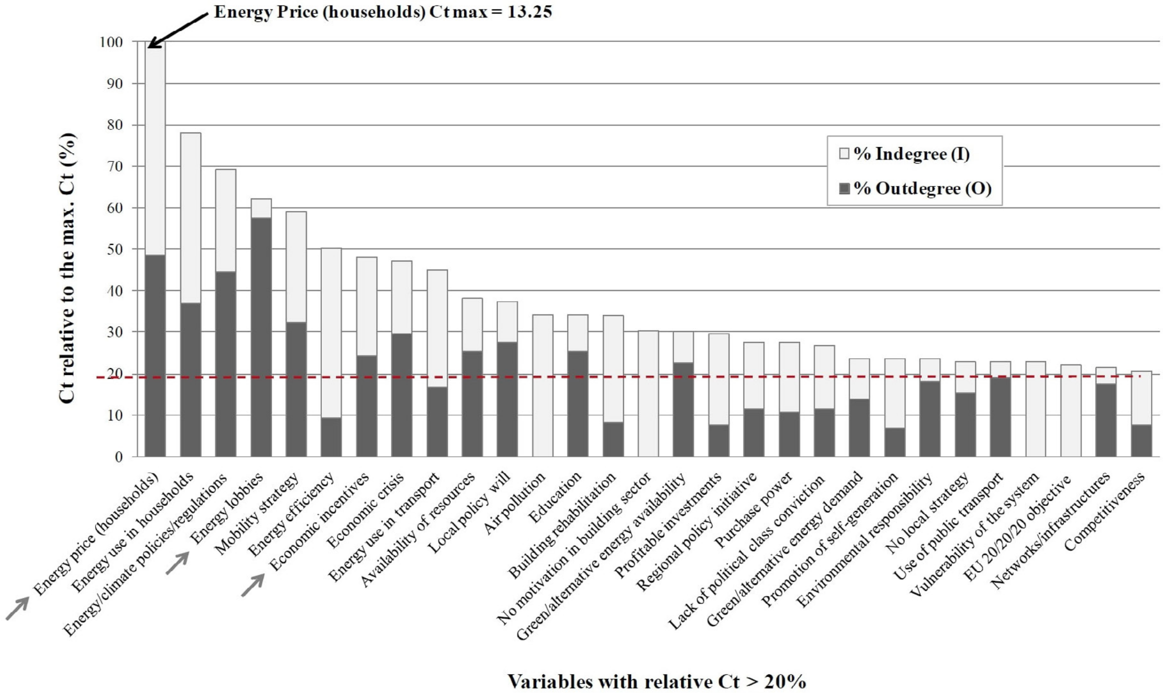

Fig. 2. Network indices

from the stakeholders' perspective this is the most strongly connected variable. In general, the variables grouped under energy "Supply & demand" (Group 9) are more central. The high Ct of some variables, such as Energy Lobbies, is due to their having a relatively high Od index, i.e., they have a high level of influence on other elements of the network. Conversely, other variables of the network, such as Energy Efficiency, owe their centrality to a high Id. Thus, Energy Efficiency plays an important role in the energy network of Tehran because of its high sensitivity to changes in a large number of other variables in the network.

Although debatable Ct as a measure of connectivity is often taken as a feature of urban resilience (Assunção et al., 2020), in the case of Tehran, the high level of network Ct in general, and specifically of some of the variables that are key entry points for low carbon management (for example energy use in households or energy use in transport), makes its energy system management complex, and is thus likely to hinder the establishing of smooth transition pathways.

It can be argued that variables with high Ct due to a high level of Od and with a low level of Id, can be used to control the behavior of the system. In this case, it is not surprising to identify the variable Energy Lobbies as that one that has the highest control level of the energy system in the city of Tehran. Other variables with high Od influence are Energy price (households), Energy use in Households and Energy/Climate policies/regulations (Figure 2).

However, these can be significantly influenced by other variables in a way that cannot be considered control variables as such. It is also interesting that, from the above-mentioned variables, only, Energy use in households and Energy/Climate policies/regulations can be controlled through community action, social awareness strategies or urban policy actions. This translates into interesting potential scenarios of transitions stimulated at local level.

Scenario analysis

An alternative transition pathway is represented in the present study by a combination of policy options that condition the state of one or more key elements of the network. For modelling purposes, this is done by fixing the value on the Od influence of one or various variables, i.e., by setting the value $A_i^{(k+1)}$. By setting a fixed value on the Od influence of a variable, all incoming influences are blocked. Variables can also be removed from the network on the hypothesis that they have no influence over the other elements in the network (Papageorgiou et al., 2020).

Three scenarios are proposed based on alternative action pathways intended to achieve a low carbon future in Tehran, based on current debates on sustainable urban transitions. In Scenario A the focus is on the use of financial incentives. An approach of using subsidies established by local government e.g., for the rehabilitating of buildings by lower income households, is maintained and the financial crisis is assumed to be overcome (fixed value=0, Table 1). In Scenario B, a transformation needs to be motivated by bottom-up initiatives and the focus is placed instead on pursuing a strong public educational and awareness campaigns. In this scenario a combined strategy to increase information to citizens, education, and awareness is implemented with the aim of analyzing the effect of social behavioral change towards a low-carbon transition. Lastly, in Scenario C, transformation needs to be catalyzed by a top-down policies and institutional motivation. This scenario is focused on strengthening local institutional initiatives so that local decision makers are the main drivers of change e.g., by strengthening the local policy framework favoring energy efficiency and climate action. Fixed values have been set arbitrarily for demonstration purposes but relatively high (between 0.7-0.9) or low (between 0-0.2) values are always maintained.

The extent of the change in each element of the network resulting from each of the three scenarios is shown in Table 2.

The percentage of variables that change under these scenarios is rather high (between 64% and 74% of change), which may be an indicator of the relatively high connectivity of the network, suggesting how complex it is to control a low carbon urban energy transition process as exemplified by Tehran. The results of Scenario A suggest a stimulus for the local economy. In this scenario, energy use declines as energy prices increase, mostly in lower income households. However, the results also show that focusing on such economic incentives does not sufficiently stimulate a change in lifestyles, which means that high-energy-consumption behavior patterns are maintained. This suggests that strategies involving financial incentives should be accompanied by other measures for example actions to address a change in current lifestyle patterns. As shown in other sustainable urban scenario case studies (Kokkinos et al., 2020) these results concur in revealing that consistent sustainability policies require multiple measures in many sectors and on many scales, not only institutionally but also socially-led. Scenario A also shows a perverse effect if the current financial incentives structure is maintained because, contrary to expectations, building rehabilitation decreases in Tehran. According to

Table 1. Scenarios and fixed values used as input for the FCMapper software

List of variables influencing scenarios	Fixed value
Scenario A: Optimization of economic incentives	
Economic crisis	0
Economic Incentives	0.8
Energy Price (households)	0.7
Scenario B: Strong education and awareness campaigns	
Ignorance of the benefits of energy efficiency measures	0.2
Information availability	0.9
Lack of awareness about the cost of resources for our economy	0.2
Lack of awareness about the impacts of consumption	0.2
Awareness/education	0.8
Social awareness	0.8
Scenario C: Stronger local institutional initiatives	
Energy/Climate policies/regulations	0.8
Local policy will	0.8
No local strategy	0.2

Table 2. Complete list of variables (classified in thematic groups) and main results of the FCM scenario and network analyses

Id	Variable	Scenario					Network[b]		
		A	B	C	B&C	MO[a]	Od	Id	Ct
	Group: 1 Environment & resources								
1	Air pollution	4	-3	-3	-3	-	0.00	4.50	4.50
2	Availability of resources	-2	2	4	4	+	3.30	1.70	5.00
3	CC mitigation	3	2	1	2	+	0.00	1.75	1.75
4	Temperate climate	0	0	0	0	+	0.90	0.00	0.90
5	Urban environmental quality	-3	3	3	4	+	0.60	1.60	2.20
6	Quality of urban space	-3	3	3	4	+	0.00	1.90	1.90
	Group 2: Innovation & opportunities								
7	Building rehabilitation	-4	2	4	4	+	1.08	3.40	4.48
8	Business/economic activity generation	3	2	1	2	+	0.00	0.20	0.20
9	Collectivizing of goods and services	-3	2	2	3	+	0.00	1.00	1.00
10	Green/alternative energy demand	4	3	1	3	+	2.95	1.00	3.95
11	Local energy producers	3	3	3	4	+	0.00	1.30	1.30
12	New development opportunities	0	0	0	0	-	0.30	0.00	0.30
13	No motivation in building sector	4	-4	-4	4	+	0.00	4.00	4.00
14	Promotion of self-generation	-3	2	2	3	+	0.90	2.20	3.10
15	Public-private partnership	3	3	3	3	+	0.80	0.80	1.60
16	R&D investment	1	1	3	3	+	0.80	0.50	1.30
17	Structured social movements	0	0	0	0	+	0.20	0.00	0.20
18	Tech availability and accessibility	0	0	0	0	+	0.80	0.40	1.20
19	Urban compatibility	-1	4	3	4	+	0.50	1.00	1.50
	Group 3: Social behavior								
20	Change in lifestyles/beliefs	-3	3	3	3	+	1.10	0.80	1.90
21	Comfort/accessibility (energy use)	-1	1	1	1	+	0.70	1.00	1.70
22	Confidence in tech	0	0	0	0	n.a.[c]	0.60	0.00	0.60
23	Consumerist leisure activities	-1	1	2	2	-	0.00	0.90	0.90
24	Disbelief in activists	-1	1	1	1	-	0.00	0.80	0.80
25	Education	-2	-	4	-	+	3.30	1.20	4.50
26	High energy-consuming lifestyles	-1	1	1	1	-	1.20	1.20	2.40
27	Ignorance of the benefits of energy efficiency measures	4	-	-2	-	-	0.00	1.30	1.30
28	Individualism	0	0	0	0	+	0.40	0.00	0.40
29	Information availability	0	-	0	-	+	0.60	0.00	0.60

Continued Table 2. Complete list of variables (classified in thematic groups) and main results of the FCM scenario and network analyses

Id	Variable	Scenario					Network[b]		
		A	B	C	B&C	MO[a]	Od	Id	Ct
30	Lack of awareness about the cost of resources for our economy	1	-	-1	-	-	0.30	0.30	0.60
31	Lack of awareness about the impacts of consumption	4	-	-2	-	-	0.30	0.80	1.10
32	Life quality perception	3	-3	-3	-3	+	0.00	0.80	0.80
33	Non-consumerist leisure activities	-1	1	1	1	-	0.00	0.05	0.05
34	Productive leisure activities	-1	1	1	1	+	0.00	0.05	0.05
35	Social awareness	0	-	0	-	-	0.70	0.00	0.70
36	Social resignation	0	0	0	0	+	0.80	0.00	0.80
37	Use of private transport	0	0	0	0	-	1.50	1.00	2.50
38	Use of public transport	0	0	0	0	+	2.50	0.50	3.00
	Group 4: Local competencies								
39	Business opening times	0	0	0	0	n.a.	1.00	0.00	1.00
40	Complex and slow procedures	0	0	0	0	-	1.50	0..00	1.50
41	Lack of political class conviction	4	-3	-3	-4	+	1.50	2.00	3.50
42	Local policy will	3	3	-	-	-	3.60	1.30	4.90
43	Mobility strategy	-3	3	4	4	n.a.	4.25	3.50	7.75
44	Shared ownership	0	0	0	0	n.a.	0.60	0.00	0.60
45	No local strategy	4	-3	-	-	-	2.00	1.00	3.00
46	Non-transcendence of scientific studies	3	-2	-2	-3	+	1.60	0.50	2.10
47	Votes	0	0	0	0	n.a.	0.70	0.00	0.70
	Group 5: Economy								
48	Competitiveness	2	2	3	3	+	1.00	1.70	2.70
49	Economic crisis	-	-4	-3	-4	-	3.90	2.30	6.0
50	Labour productivity	1	-1	-3	-3	-	0.00	0.15	0.15
51	Local private economic interests	-1	1	3	3	+	0.50	1.00	1.50
52	Profitable investments	4	4	2	4	+	1.00	2.90	3.90
53	Purchase power	4	4	-2	4	+	1.40	2.20	3.60
54	Short-circuit economies	0	0	0	0	+	2.00	0.00	2.00
55	Vulnerability of the system	-3	-2	-3	-3	-	0.00	3.00	3.00
	Group 6: Life basics								
56	Culture & knowledge	-1	1	1	1	+	0.00	0.40	0.40
57	Food	-1	1	2	2	+	0.00	0.20	0.20
58	Human safety & protection	-1	1	2	2	+	0.00	0.70	0.70
59	Hygiene	-1	1	1	1	-	0.00	0.07	0.07
60	Learning	-1	1	1	1	+	0.00	0.03	0.03
61	Leisure & fun	-1	1	3	3	+	1.00	0.20	1.20
62	Life & survival	-1	1	3	3	-	1.00	0.30	1.30
63	Personal development	-1	1	2	2	+	1.00	0.10	1.10
	Group 7: Governance								
64	Economic incentives	-	3	4	4	+	3.20	3.10	6.30
65	Electric network toll	0	0	0	0	n.a.	0.60	1.00	1.60

Continued Table 2. Complete list of variables (classified in thematic groups) and main results of the FCM scenario and network analyses

Id	Variable	Scenario					Network[b]		
		A	B	C	B&C	MO[a]	Od	Id	Ct
66	Energy/climate policies/regulations	-3	3	-	-	+	5.85	3.25	9.10
67	Environmental responsibility	-3	3	3	4	+	2.40	0.70	3.10
68	EU 20/20/20 objective	-4	4	4	4	+	0.00	2.90	2.90
69	Law on "balance neto"	0	0	0	0	+	0.70	1.00	1.70
70	National strategy on energy sources	0	0	0	0	-	0.80	0.00	0.80
71	Public budget	4	4	2	4	-	0.00	1.00	1.00
72	Regional policy initiative	2	2	4	4	+	1.50	2.10	3.60
	Group 8: Supply & demand								
73	Energy efficiency	2	4	4	4	+	1.20	5.40	6.60
74	Energy price (households)	-	2	3	3	+	6.38	6.75	13.13
75	Energy price (industry)	2	-2	-4	-4	-	0.90	1.00	1.90
76	Energy use in households	4	-4	-4	-4	-	4.85	5.40	10.25
77	Energy use in industry	0	0	0	0	-	0.50	0.00	0.50
78	Energy use in municipal services	-2	-2	-4	-4	-	0.25	0.50	0.75
79	Energy use in transport	4	-4	-4	-4	-	2.20	3.70	5.90
80	Energy used in non-material resources	1	-1	-3	-3	-	0.00	0.25	0.25
	Group 9: Energy business								
81	Energy lobbies	0	0	0	0	-	7.55	0.60	8.15
82	Energy security	-1	1	1	1	+	0.80	0.60	1.40
83	Green/alternative energy availability	4	3	1	3	+	2.95	1.00	3.95
84	Networks/infrastructures	-1	1	1	1	n.a.	2.30	0.50	2.80
85	Specialized technical energy services	0	0	0	0	+	1.60	0.00	1.60
86	Technical inspections	0	0	0	0	n.a.	0.50	0.00	0.50

[a] M.O., Sustainable management objectives.
[b] Network characteristics: Od, Out-degree; Id, In-degree; Ct, Centrality.
[c] n.a., not applicable.

various stakeholders, experience in Tehran reveals that as financial incentives are not targeted at higher income households, their benefits (lower energy use, greater comfort) are often not sufficiently perceived by the majority of property owners, at least in the short term.

Scenario B is driven by strong education and awareness campaigns. It provides better results than Scenarios A or C. In this scenario, the strategy is designed to increase information to citizens, education, and awareness so that the benefits of potential social behavioral change and its contribution to a low-carbon transition can be studied. The results of scenario B suggest that education, knowledge and awareness about current urban problems can result in the strengthening of local initiatives and an improvement in the local economy, especially in terms of attracting businesses related to renewable energy. Scenario C is primarily focused on giving a key role to local authorities in driving the low-carbon transition by delivering energy and climate policies, regulations and building an urban strategy towards sustainability and resilience. This scenario also has good results but still suggests potential unintended effects such as an increase in household energy bills.

Given the large number of potential unintended effects of one-sided strategies which might

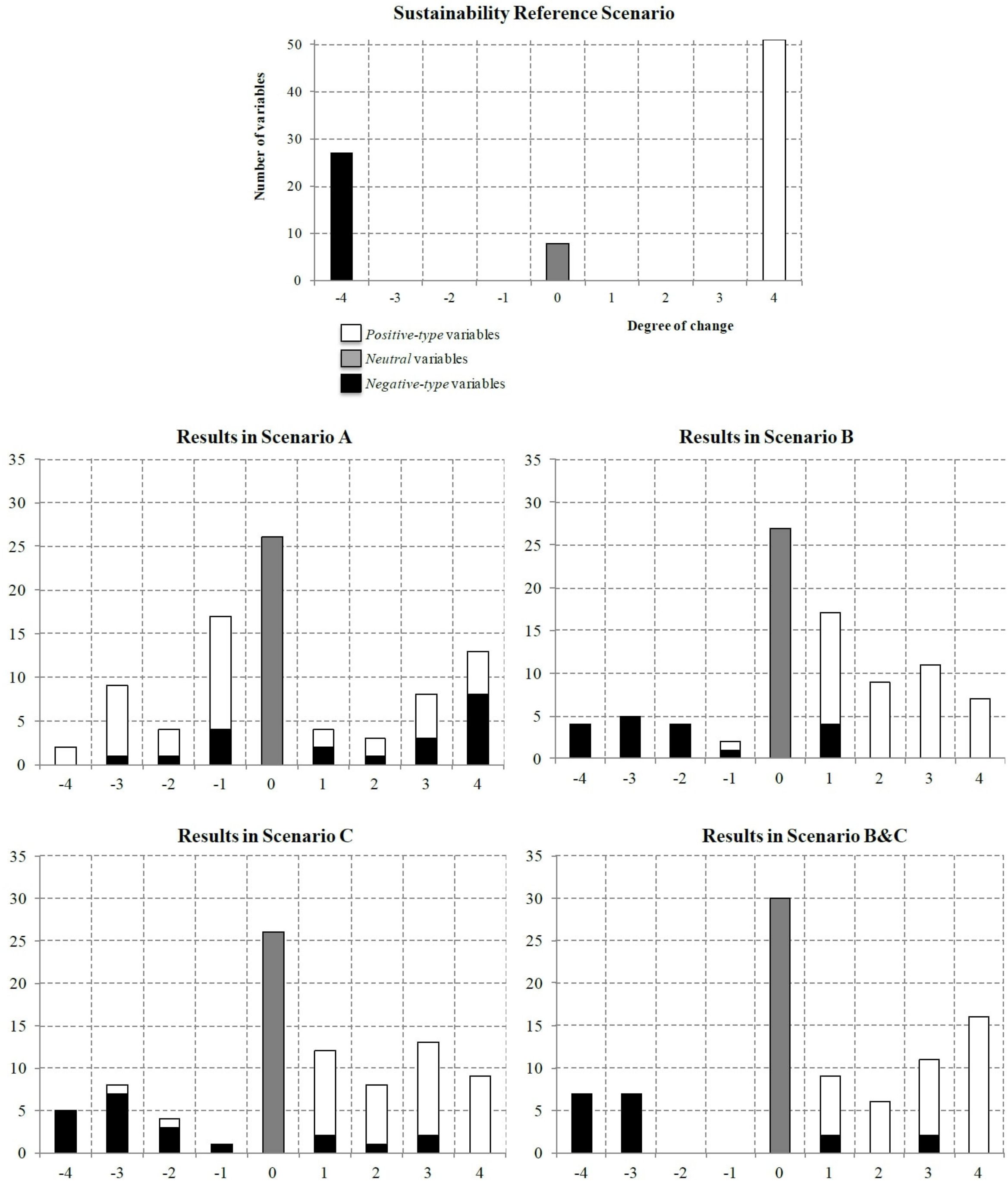

Fig. 3. Comparison of scenarios against the sustainability reference scenario

(Alipour et al., 2019), according to collective knowledge, result in undesirable or unstable transitions, and given the important role of social movements in building adaptive capacity (Papageorgiou et al., 2020), a combined scenario, scenario B&C is suggested. This scenario combines scenario B, representing bottom-up social action, and scenario C, representing top-down local institutional action.

Figure 3 presents a comparison the 3+1 scenarios created with a sustainability reference scenario developed ad-hoc for the case study. In this scenario, the 86 variables are grouped into three sets (positive, neutral or negative) depending on the desirable management objective (MO) in terms of sustainability for each variable (Table 2). Clearly, this desirable MO must not be taken as a general reference as it serves merely for purposes of comparison in this study, in line with the authors' experience in the specific context of Tehran. According to this sustainability reference scenario, on the one hand there are variables that are associated with positive change (scaled from 1, minimum change, to 4, maximum positive change, relative to their original values) from a sustainability and resilience perspective (e.g., Availability of resources). These are referred to hereafter as positive-type variables. On the other hand, there are variables that are associated with negative change (scaled from -1, minimum change, to -4, maximum negative change, relative to their original values) from a sustainability and resilience perspective (e.g., Energy use in households). These are referred to hereafter as negative-type variables.

Establishing a desirable sustainable objective for each variable might be difficult given that variables are not always verbalized in a positive sense (e.g., No local strategy). The FCM contains 51 positive-type variables and 29 negative-type variables under a sustainability reference scenario for the Tehran case study. Eight variables are considered neutral i.e., they are not expected to undergo any significant change and their value is zero (Figure 3). Positive-type variables are optimally located on the right side, which means that the more positive-type variables there are on the right-hand side of the Figure 3 the greater the beneficial change that can be expected is. The most sustainable, most resilient location for negative-type variables would be the left-hand side of the Figure 3. Hence the more negative-type variables there are located on the left, the greater the beneficial change is in terms of a transition to a sustainable urban energy system in Tehran.

Based on this assessment, the combined scenario B&C provides better results than either B or C individually under two criteria, sustainability outcome and agency of change. In scenario B&C none of the positive-type variables decreases under the influence of the new system conditions. In addition, slightly fewer negative-type variables increase. Both these facts result in a higher sustainability outcome. Also, the number of variables that remain unchanged significantly increases, which could be interpreted as the result of better control and agency in the process of transformation. All in all, this agency in scenario B&C is achieved at the expense of a decrease in the number of positive-type variables that change positively.

CONCLUSION

According to collective knowledge gathered through the individual fuzzy cognitive maps, the results of the case study in Tehran suggest that a combination of top-down and bottom-up action provides greater sustainability in the new system. Factors such as the cost of implementing these policies and their robustness in the long are critical if any energy transition plan is to be developed in a city. Further, the research findings showed the evidence of the two-sided perspective of resilience. Connectivity of the network might be a double-edged sword. On the one hand, connectivity may be desirable as may translate into more seeds of change and could therefore provide more opportunities for self-organization after a shock if a process of transformation is undertaken. On the other hand, when there is a high level of connectivity, there might be more non-linear feedbacks, thus, change and transformation might be more difficult to control.

For example, in Scenario A, due to high connectivity and the centrality of key elements of the network, the urban energy system in Tehran may be highly resilient to financial changes i.e., in individual income or public budgets. But it finds that while economic incentives show a high level of connectivity within the network, the scenario analysis suggests that it can also lead to undesired impacts such as an increase in air pollution. In other words, the energy system is unlikely to undergo a process of transformation towards sustainability through economic incentives alone. In fact, such approach may lead to 'mal-transformation', restating dependency on energy consumption and thus leading to a deeper lock-in regarding unsustainable patterns of energy consumption. Also, reinforced positive impacts are obtained by combining local-institutional and community initiatives that fuel higher levels of environmental education, awareness and responsibility among citizens (i.e., Scenario B&C). Positively, in this combined scenario we have observed that there is an increase in the number of 'neutral' variables (variables that remain unchanged) which might also indicate a weakening in the connectivity of the system which might be seen as an uptake of a meaningful change towards a low carbon transition.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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