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Jessica Belest
EURAC Research, Italy

Laura Secco
University of Padua, Italy

Elena Pisani
University of Padua, Italy

See next page for additional authors

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Authors
Jessica Belest, Laura Secco, Elena Pisani, and Alberto Caimo

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Sustainable energy governance in South Tyrol (Italy): A probabilistic bipartite network model

J. Balest [a, b, *], L. Secco [b], E. Pisani [b], A. Caimo [c]

[a] EURAC Research, Italy
[b] Department of Land, Agriculture, Environment, and Forestry, University of Padua, Italy
[c] School of Mathematical Sciences, Technological University Dublin, Ireland

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ABSTRACT

At the national scale, almost all of the European countries have already achieved energy transition targets, while at the regional and local scales, there is still some potential to further push sustainable energy transitions. Regions and localities have the support of political, social, and economic actors who make decisions for meeting existing social, environmental and economic needs recognizing local specificities.

These actors compose the sustainable energy governance that is fundamental to effectively plan and manage energy resources. In collaborative relationships, these actors share, save, and protect several kinds of resources, thereby making energy transitions deeper and more effective.

This research aimed to analyse a part of the sustainable energy governance composed of formal relationships between municipalities and public utilities and to investigate the opportunities to further spread sustainable energy development within a region.

In the case study from South Tyrol, Italy, the network structures and dynamics of this part of the actual energy governance were investigated through a social network analysis and Bayesian exponential random graph models.

The findings confirmed that almost all of the collaborations are based on spatial closeness relations and that the current network structures do not permit a further spread of the sustainable energy governance.

The methodological approach can be replicated in other case studies and the findings are relevant to support energy planning choices at regional and local scales.

1. Introduction

Global, regional, and local environmental organizations maintain that there are two choices to make in the world: on the one hand, organizations can work for a sustainable world (Sachs, 2015; Keeble, 1988); on the other, organizations can dismiss sustainable, zero or de-growth development and increase pollution and ecological pressures on the natural and social worlds (Vandenhole, 2018).

Based on cleaner production and energy transition processes, sustainability addresses persistent environmental, social, and economic problems, needs (Geels, 2011) and dimensions (Cîrstea et al., 2018). Strezov et al. (2017), underline that human beings must consider the reality of resource limitations, the capacities of ecosystems, and the needs of future generations. Sustainability is strictly connected to the support of a community (Macgregor, 2003) and of linked organizations and is also fundamental to the energy sector. In sustainable development and its three main dimensions, energy sustainability is salient for reducing poverty, raising living standards, and improving human well-being (Cîrstea et al., 2018).

The practice of carefully using natural resources for renewable energy production is globally recognized and represents a common objective (Jänicke, 2017; Leal Filho et al., 2016), even when competing with other economic, financial, and global dynamics (Medeiros, 2016; Sassen, 2004). The sustainability of regional and local energy governance has allowed political, social, and economic actors to use local resources to meet existing social, environmental, and economic regional and local needs (Europena Commission,

* Corresponding author. EURAC Research, Via A.Volta 13/A, Bolzano, Italy.
E-mail address: jessica.balest@eurac.edu (J. Balest).

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2014; Geels, 2011). The political, social, and economic actors at the regional and local scales are important because of their closeness to the local context and for their ability to recognize local specificities (i.e., natural energy potential) (Jänicke, 2017). These actors (i.e., states, municipalities, organizations of civil society, enterprises) compose an energy governance that is able to achieve sustainability while making decisions at the regional and local scale.

Sustainable energy development is the result of this network of actors who make sustainable decisions and compose an energy governance coalition. Governance is an arena in which multi-actor, multi-sector, and multi-level relationships, power relations, and networking exist (Secco et al., 2014; Rametsteiner, 2009) with the aim to administer sectors of public and social life. The energy sector at regional and local scales is managed by authorities, enterprises, and organizations of civil society. In the public sector, regional and local authorities (i.e., municipalities) plan the production, distribution, and consumption through regional and local energy planning processes (Novotná et al., 2016; Bulkeley and Kern, 2006). These authorities can be supported by enterprises or organizations of civil society that have, at least in the Italian context, the formal structure of public utilities (PUs) or cooperatives (Coelho et al., 2018; Magnani and Osti, 2016; Heldeweg et al., 2015). The analysis of energy governance at regional and local scales is a relevant topic in promoting the change to a more sustainable world (Sachs, 2015). Therefore, in this research, the term sustainable energy governance was used to identify the network of actors that make sustainable decisions in the energy sector at regional and local scales, with a focus on municipalities and PUs as relevant actors (Fudge et al., 2016).

The PUs are relevant actors that manage the competition and other relational dynamics between municipalities, increasing the opportunities to plan and manage the energy sector (Coelho et al., 2018). The collaborations between municipalities and the PUs are an important and structured relationship that formally supplies energy services to local populations (Mejía-Dugand et al., 2017). The PUs are not the only actors involved in energy governance: other direct collaborations between municipalities and with structured (i.e., energy cooperatives) or unstructured actors (i.e., other regional and local stakeholders) mobilize local resources.

At the local scale, the collaborations between actors (i.e., governance involving municipalities and PUs) (Niesten et al., 2017; Leal Filho et al., 2016) mobilizes the pursuit of choices that are sustainable in the local territory (Jänicke, 2017). Collaborative relationships in the regional and local context "build settings where trust and reciprocity can emerge, grow, and be sustained over time" (Ostrom, 2010). These settings promote costly and positive decisions and actions without waiting for an external authority to impose rules, monitor compliance, and assess penalties. For this reason, initiatives and actions from the local actors can accelerate the energy transition using local resources in a sustainable way and emphasize the resilience and sustainability of the territories (Ostrom, 2010), supporting the wider global and national energy transition.

Trust and reciprocity emerge where actors had prior experiences of collaboration (Nielsen, 2004). In the case of local authorities, collaborations usually exist between spatially close and neighbouring municipalities. The importance of collaborations among similar municipalities for effective and sustainable energy planning and management (Medeiros, 2016; European Commission, 2008) goes further than the simple neighbourhood. Furthermore, the borders of the municipalities represent a separation and sometimes a competition based on power and autonomy between the municipalities. The European Commission (2008) stresses the search of energy governance, which overtakes borders and collaborations of neighbouring territories.

This research focused on formal relationships and sustainable energy governance defined a group of municipalities (the closest authority to local specificities) within a region that collaborate with one another in the energy sector in a sustainable way, supported by PUs. This paper focused on the relational elements at local levels in order to investigate the opportunities to extend sustainable energy governance and to strengthen its sustainable features. Even if the sustainability concept is broad and does not only include only the meaning considered in this paper (Leal Filho et al., 2016; Geels, 2011), this research tested some of the hypotheses related to elements of sustainability described in this introduction.

The first hypothesis tested is that a municipality does not use, plan, and manage the energy through collaborations with other municipalities and that it prefers to work with an economic actor, such as a PU **(Hypothesis 1)**. In cases where collaborative relationships exist, the hypothesis is that formal relationships among municipalities and PUs are more likely to be observed when municipalities are spatially close and already have trust relationships **(Hypothesis 3)**. However, the European Commission is interested in understanding the opportunities for collaborative planning and management based on common resources. The hypothesis is that formal relationships among municipalities and PUs are more likely to be observed when municipalities belong to the same geomorphological context **(Hypothesis 2)** sharing common natural local resources for use in energy production, i.e., natural energy potential in terms of the urban, forest, and agriculture land covers and solar radiation sites **(Hypothesis 5)** (Medeiros, 2016; European Commission, 2008). Having few and clear needs, the municipality would prefer to work with one PU per need, energy source, or energy potential: contractual relations among municipalities and PUs are less likely to be observed when a PU has equal or similar energy activities **(Hypothesis 4)**. On a practical level, formal relationships based on contracts between municipalities and PUs in the energy governance, their characteristics, the relevant relational dynamics, and the probability to observe new relationships between municipalities and PUs were investigated.

These hypotheses were tested using a Bayesian exponential random graph modelling (ERGM) approach (Caimo and Friel, 2011) for bipartite networks. Exponential random graph models represent an important family of log-linear network models that aim to describe the probability distribution of the edges among pairs of nodes in a network using a set of network configurations. A Bayesian exponential random graph model was applied to the South Tyrol case study.

The South Tyrol case study is interesting for its commitment to energy transition (i.e., Provincial Climate and Energy Plan, 2050) and its partial freedom from national energy legislation in as compared with other Italian regions. South Tyrol is an autonomous province in North-East Italy and it has energy governance based on collaborations between 120 PUs and 116 municipalities.

This paper was the first application of the statistical network analysis approach with the aim to model sustainable energy districts. Even if this research has a gap in not considering the informal relationships between municipalities, its methodology can be replicated in other case studies and its results can be used by the provincial and local energy planners and managers of South Tyrol. Based on the results of this research, energy planners and managers could address new collaborations in the energy sector and make changes in the energy governance for the wider achievement of international and provincial energy transition goals.

2. Material and methods

2.1. Energy governance network data in South Tyrol

The previous hypothesis (Table 1) and Bayesian inference for

Table 1
List of hypothesis tested in this research.

Hypothesis
Hypothesis 1: Municipalities do not collaborate with other municipalities but they prefer individual support from PUs
Hypothesis 2: Relationships between municipalities based on contracts with PUs are more likely to be observed when municipalities belong to the same geomorphological context
Hypothesis 3: Relationships between municipalities based on contracts with PUs are more likely to be observed when municipalities are spatially closed
Hypothesis 4: Municipalities have contracts with more PUs when PUs have different energy activities
Hypothesis 5: Relationships between municipalities based on contracts with PUs are more likely to be observed when municipalities have the same natural energy potential (i.e., forest land cover)

ERGMs were tested into a case study in the South Tyrol area. South Tyrol is an area located in Northeastern Italy and composed of 116 municipalities. The municipalities are represented by cycles linked to 120 PUs that are represented by triangles in Fig. 1.

Some municipality's characteristics were considered, i.e., geomorphological valleys, land cover, and solar radiation (Table 2), according to the hypothesis (Table 1).

2.2. Bipartite network data

This is a two mode-network composed by first (municipalities) and second (PUs) modes, with uniplex relations (Fig. 1). The uniplex is based on relations based on a service contract for delivery of energy services or goods, and moreover, there is an arrow from the municipality to the PU in terms of contractual duties based on the contract. Accordingly, this network is represented as an undirected graph and all the relations between the two modes can be represented without specifying the arrows. The high number of isolated nodes represents the lack of interest of the municipalities (circles) to be supported by national or local PUs in the energy sector.

2.3. Hypothesis

In this analysis of the relational dynamics, defined as small network structures or configurations, some hypotheses were investigated (Tables 1, 3 and 4). Hypothesis 1 was tested by investigating the existence of edges, isolated nodes, and the degree density. Hypothesis 2 was investigated through the homophily of the municipalities in terms of the geomorphological context: if two or more municipalities belong to the same geomorphological valley, they have already collaborated and they have already built a trust (or distrust) that renovates old and new collaborations (Nielsen, 2004). Hypothesis 3 was investigated through the homophily of municipalities. As with hypothesis 2, the same dynamics are hypothesized here: collaborations are more likely between spatially close municipalities. Hypothesis 4 was investigated through homophily of the PUs, in terms of their main activities. PUs are means of collaboration for answering to different municipalities' and local populations' needs: more PUs with the same energy activities would cause duplications. Finally, hypothesis 5 was investigated through the homophily of municipalities on the nature and the similarities of renewable sources. The site-specific nature of renewable sources is described as urban, forest, and agriculture

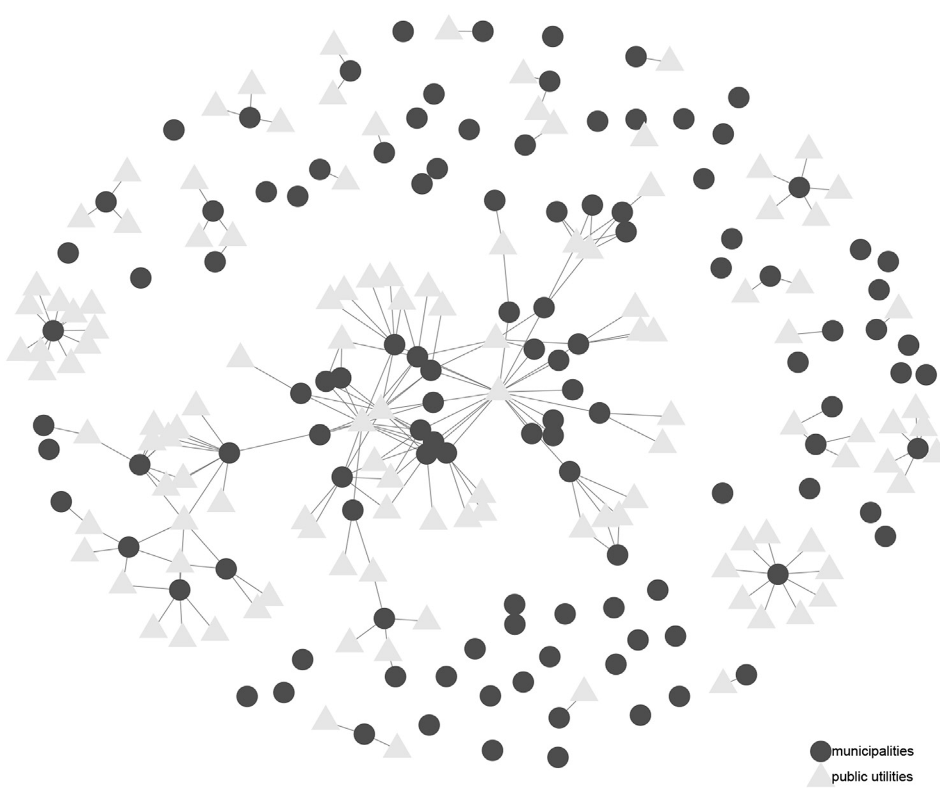


Fig. 1. The graph represents the municipalities (circles), the public utilities (triangles), and the relationships between them (lines).

Table 2
Data description and sources used in this research.

Data	Description	Year	Case study	Source
Network data	Relationships between municipalities and public utilities in the energy sector	2016	South Tyrol	Ministry of Economics and Finance data source
Geomorphological valley and closeness	Geomorphological valley, longitude and latitude. An index on the closeness between municipalities is calculated	2016	South Tyrol	Ancitel open data : own elaboration[a]
Urban, agriculture, and forest land cover	The percentage of each type of land cover out of the total surface. The indices are calculated based on the CORINE database and bordering of municipalities	2016	South Tyrol	CORINE Land Cover, Ancitel open data: own elaboration[a]
Solar radiation	Mean of solar radiation	2016	South Tyrol	PVGIS: own elaboration

[a] The weblink does no longer exist. Data can be found in www.dossier.net and www.comuni-italiani.it.

Table 3
The table lists model specifications in terms of endogenous statistics.

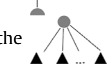
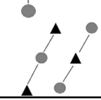
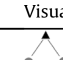
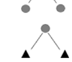
Hypothesis	Statistics name	Attribute	Description	Visualization
Hypothesis 1	edges	None	Number of edges in the network	
Hypothesis 1	gwb1degree	None	Weighted degree distribution for nodes in the first mode (municipality) of the bipartite network. It gives an idea of the equal distribution of nodes or distribution around a few central nodes in the network	
Hypothesis 1	isolates	None	Number of nodes with degree zero	
Hypothesis 1	b1degree(1)	None	Number of nodes of degree 1 in the first mode (municipality) of the bipartite network. The representation is the same on the edge, but in this case degree 1 is represented only by the figure and not the figure included in other configurations	
Hypothesis 1	degree(2)	None	Number of nodes in the network of degree 2, with exactly 2 edges	

Table 4
The table lists model specifications in terms of covariate statistics.

Hypothesis	Statistics name	Attribute	Description	Visualization
Hypothesis 2	b1nodematch	Valley	Nodal valley-based homophily effect for the first mode (municipality) in the bipartite network	
Hypothesis 5	b1nodematch	Urban land cover	Nodal urban land cover-based homophily effect for the first mode (municipality) in the bipartite network	
Hypothesis 5	b1nodematch	Forest land cover	Nodal forest land cover-based homophily effect for the first mode (municipality) in the bipartite network	
Hypothesis 5	b1nodematch	Agriculture land cover	Nodal agriculture land cover-based homophily effect for the first mode (municipality) in the bipartite network	
Hypothesis 3	b1nodematch	Closeness	Nodal closeness-based homophily effect for the first mode (municipality) in the bipartite network	
Hypothesis 5	b1nodematch	Radiation	Nodal radiation-based homophily effect for the first mode (municipality) in the bipartite network	
Hypothesis 4	b2nodematch	Activity	Nodal activity-based homophily effect for the second mode (PUs) in the bipartite network	

land covers and solar radiation (Garegnani et al., 2018; Sacchelli et al., 2013). When two or more municipalities share similar renewable sources, they build shared objectives and projects for equal development (Medeiros, 2016; European Commission, 2008).

Based on these hypotheses, the Bayesian exponential random graph model (BERGM) was applied to the network of collaborations between municipalities and PUs in South Tyrol.

2.4. Exponential random graph models (ERGMs)

Typically, networks consist of a set of actors and relationships between pairs, for example social interactions between individuals. The relational structure or configuration of a network graph is described by a random adjacency matrix Y of a graph of n nodes (actors) and a set of edges (relationships) $\{Y_{ij} : i = 1, \ldots, n; j = 1, \ldots, n\}$ where: The

$$Y_{i,j} = \begin{cases} 1, & i \sim j; \\ 0, & i \nsim j. \end{cases}$$

ERGMs are a particular class of discrete linear exponential families, which represent the probability distribution of network graphs on n nodes as:

$$p(y|\theta) = \frac{\exp\left\{\theta^t s(y)\right\}}{z(\theta)},$$

where $s(y)$ is a known vector of sufficient statistics, θ are the associated model parameters, and $z(\theta)$ is a normalising constant which is difficult to evaluate for all but trivially small graphs. The dependence hypothesis at the basis of these models (Table 1) is that edges self-organize into small network structures called configurations. There is a wide range of possible network configurations (Robins et al., 2007), which allows the flexibility to adapt to different contexts. A positive parameter value for θ_i results in a tendency for a certain configuration corresponding to $s_i(y)$ to be observed in the data that is otherwise expected by chance.

2.5. Bayesian inference for ERGMs

The growing interest in Bayesian techniques for the analysis of social networks can be attributed to the development of efficient computational tools and the availability of user-friendly software. Bayesian analysis is a promising approach to statistical network analysis because it yields a rich picture of the uncertain quantities, a picture which is essential when dealing with complex statistical network models and heterogeneous relational data. Using a Bayesian framework leads directly to the inclusion of prior information about the network structure into the modelling framework, and provides immediate access to the uncertainties by evaluating the posterior distribution of the parameters.

A Bayesian inference for ERGMs is based on the posterior distribution of θ given the data y:

$$p(\theta|y) = \frac{p(y|\theta)\, p(\theta)}{p(y)} = \frac{\exp\left\{\theta^t s(y)\right\}}{z(\theta)} \frac{p(\theta)}{p(y)},$$

where $p(\theta)$ is a prior distribution that assigns a probability distribution reflecting prior beliefs about the values of the parameter before analysis of the data, and $p(y)$ is the evidence or marginal likelihood of y which is typically computationally intractable.

Standard MCMC (Markov Chain Monte Carlo) methods such as the Metropolis-Hastings algorithm, can deal with posterior estimation as long as the target posterior density is known up to the model evidence $p(y)$. Unfortunately, in the ERGM context the posterior density $p(\theta|y)$ includes two intractable normalising constants, the model evidence $p(y)$ and $z(\theta)$. For this reason, the ERGM posterior density is computationally 'doubly intractable'.

To carry out Bayesian inference for ERGMs, the Bergm package (Caimo and Friel, 2014) for R makes use of a combination of Bayesian algorithms and MCMC techniques including the approximate exchange algorithm which circumvents the problem of computing the normalising constants of the ERGM likelihoods, while the use of multiple chains and efficient adaptive proposal strategies are able to speed up the computations and improve chain mixing quite significantly (Caimo and Friel, 2011, 2013; Caimo and Mira, 2015). This research made use of the fast pseudo-posterior correction approach proposed by (Bouranis et al., 2017) to estimate the posterior distribution of the ERGM parameters.

2.6. Model specifications

Given the hypothesis included in Table 1, our main model specifications are listed in Tables 3 and 4. The (exogenous) statistics that have an attribute are closely related to our hypothesis (Table 4), while the statistics without an attribute (endogenous) (Table 3) overlook the characteristics of the network and better fit the goodness of the model (Caimo and Lomi, 2014; Caimo et al., 2017).

2.7. Software

The R code implementing the methodology proposed in this paper makes use of the Bergm package (Caimo and Friel, 2014) to analyse the bipartite structure of the observed network graph and is currently available on GitLab.

3. Results and discussion

3.1. Posterior estimates

For the analysis, a vague prior distribution for all the parameters was used, i.e., $\theta_i \sim N_d(\mu, \Sigma)$, where the dimension d corresponds to the number of parameters, μ is a mean vector centred at 0 and Σ is a $d \times d$ diagonal covariance matrix whose variances are all set to equal 100.

The posterior estimates of the parameters explains the importance of the corresponding network statistics in examining the overall connectivity structure of the observed bipartite network. The lines in bold in Table 5 represent the posterior parameter summaries for which 0 does not fall within the credible intervals. This means that the bold posterior parameters are relevant in explaining the actual network, considering the whole model.

The model investigates the diffusion of energy governance collaborations based on relationships between municipalities and PUs, and underlines the practices under the energy governance in South Tyrol. The actual network (Fig. 1) has a low density characterised by few edges (θ_1, θ_2, θ_4 in Table 5) and 53 isolated municipalities (θ_3 in Table 5). This means that collaborations among municipalities and PUs with the aim to plan and manage the energy sector at local scales exist but they are not used by almost half of the municipalities. Therefore, the research partly confirms Hypothesis 1 of Table 1: the values of edges (θ_1), and the network density (θ_2, θ_4) are low (Table 5), counting 53 out of 116 municipalities that do not use, plan, and manage their energy through energy services supplied by PUs. Further, the presence of PUs that supply the services for only one municipality is relevant (θ_5), partly confirming the second part of Hypothesis 1 of Section 2.3: the municipalities that use, plan, and manage energy prefer to be individually supported by PUs. The practice of collaborating between municipalities by means of shared PUs is only partly spread (θ_5) and involves only 32 out of 120 PUs.

Deepening the practice to collaborate includes the characteristics of actors, the so called covariate statistics (Table 4), and the practice of collaborate among similar ones; this research defined some relevant shared features of municipalities. Looking at Table 5 and its θ_6, θ_{10}, and θ_{11}, the municipality attributes of valley, spatial closeness, and solar radiation are relevant to explain the two-star configurations: Two municipalities share the same PUs when they are close to one another, belong to the same valley and have similar ranges of solar radiation. The two-star configurations based on the urban, forest, and agriculture land cover characteristics of

Table 5
Posterior mean, median and 95% credible intervals.

Parameter (statistic)	Mean	Median	2.5%	97.5%
θ_1 **(edges)**	**−4.7247**	**−4.7364**	**−5.5080**	**−3.9151**
θ_2 **(gwb1deg)**	**−6.7181**	**−6.6652**	**−9.0727**	**−4.7058**
θ_3 **(isolates)**	**−6.8594**	**−6.7607**	**−9.9957**	**−4.2771**
θ_4 **(b1deg1)**	**−2.6944**	**−2.6720**	**−3.9257**	**−1.5968**
θ_5 **(degree2)**	**−0.9822**	**−0.9859**	**−1.4762**	**−0.4855**
θ_6 **(b1nodematch.valley)**	**1.1404**	**1.1486**	**0.2605**	**1.9892**
θ_7 (b1nodematch.urban.clc)	0.4278	0.4395	−0.3964	1.2220
θ_8 (b1nodematch.forest.clc)	0.5629	0.5633	−0.4048	1.4964
θ_9 (b1nodematch.agric.clc)	−0.0249	−0.0248	−1.0123	0.9727
θ_{10} **(b1nodematch.closeness)**	**1.2382**	**1.2267**	**0.5752**	**1.9529**
θ_{11} **(b1nodematch.radiation)**	**0.8199**	**0.8146**	**0.0770**	**1.5745**
θ_{12} (b2nodematch.PU.nature)	−0.2243	−0.2255	−0.8980	0.4538

The bold values represent the posterior summaries for the parameters whose 95% credible intervals do not include 0.

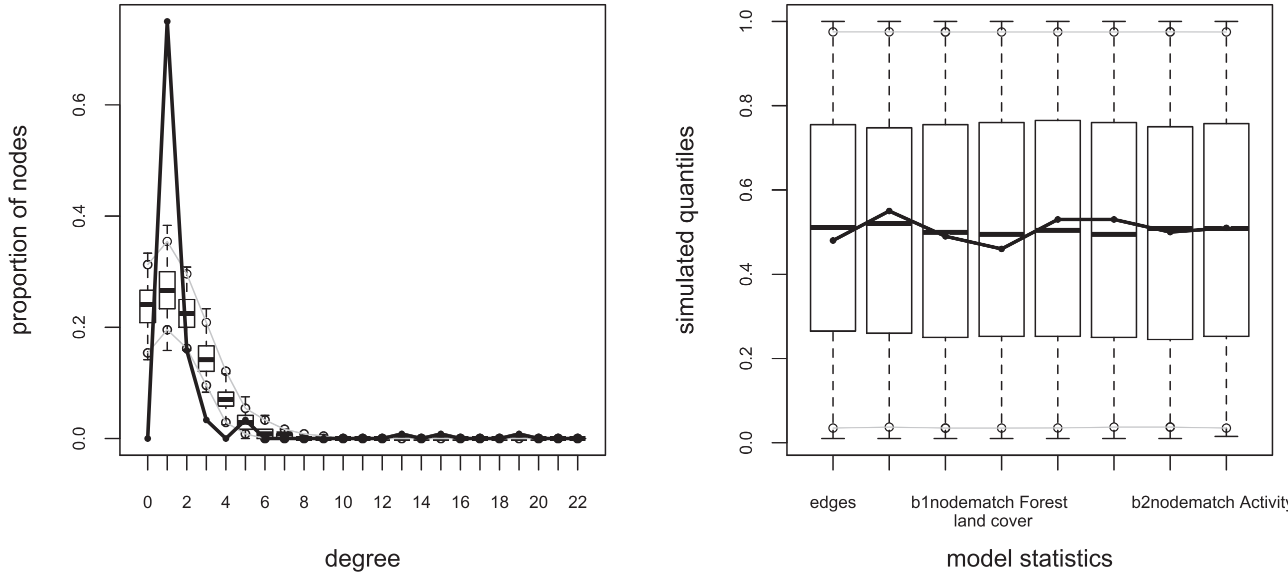


Fig. 2. Goodness of fit diagnostics of the first model including only covariate statistics. *edges, b1nodematch Forest land cover, and b2nodematch Activity* are three statistics of those explained in Tables 3 and 4

municipalities (Table 4) are not relevant to explain the actual network, and the activities of the PUs are not relevant to explain the network configuration. The practice of collaborating with similar parties was only confirmed by considering the geomorphological context (Hypothesis 2 of Table 1), spatial closeness (Hypothesis 3 of Table 1), and solar radiation characteristics (partially confirming Hypothesis 5 of Table 1). Hypothesis 4 and portions of Hypothesis 5 were not confirmed in the South Tyrol energy governance. According to the results, the practice of local government recognizes solar radiation as a local resource to use as a means to collaborate with other municipalities for planning and managing energy. This could be due to a multiplicity of tools in South Tyrol for energy planners that increase the awareness about the solar radiation resource (Rete Civica dell'Alto Adige), while other results should not be expected in regions where this awareness is weaker. Several studies on urban, forest, and agriculture land cover and energy potential have been done for the South Tyrol area, but no online results are available. This may mean that energy planners and managers do not have enough information on urban, forest, and agriculture potentialities to build *ad hoc* collaborations. Furthermore, a common range of solar radiation can describe similar morphological characteristics but, in this case, not for similar (urban, forest, and agriculture) land cover and natural energy potentials. Finally, the individual features of the solar plants can support collaborations across municipal borders, while for example, collective features and an energy distribution to a group of households characterize the biomass and biogas plants.

3.2. Goodness-of-fit diagnostics

A way to examine the fit of the data to the posterior model and the output obtained is to implement a Bayesian goodness-of-fit procedure (Hunter et al., 2008). To do this, network graphs were simulated from independent parameter values randomly drawn from the estimated posterior distribution and compared to the observed network data in terms of high-level characteristics that are not modelled explicitly. In this context, since the research was dealing with a bipartite network, the focus was on the degree distribution.

The black solid lines represent the distributions of the observed data. The boxplots represent the goodness-of-fit distributions calculated on 100 network graphs simulated from the ERGMs based on values sampled from the estimated posterior distribution. The solid light grey lines mark the 95% intervals. An estimated ERGM fits perfectly within a certain observed network if the black line falls inside this interval – a result that is very difficult to obtain in practice.

Figs. 2, 3 and Table 3 show that the model, including the extra-dyadic endogenous network statistics,[1] better fits the actual network with respect to the model including only covariate statistics.

3.3. The relevance of bridges and their probability to exist

The model and its estimates were not only relevant to understand the network dynamics under the actual relationships. Based on model estimates, this research could investigate the probability of observation of each edge compared to the probability of not being observed (odds), when it exists and when it does not exist. Once the findings confirmed that only 63 out of the 116 municipalities are supported by PUs, the research questioned the opportunities to spread this practice. Bridges can be a means to spread energy governance practices to the isolated nodes.

In particular, some existing edges have a low probability of being observed (conditional on the rest of the network structure being fixed), while almost all of the non-existent edges have a low probability of being observed. In the first case, the existing and low likely edges follow dynamics that the model did not consider (i.e., a conflict between the municipality and a PU). The model was not able to explain why some edges exist. *Vice versa*, the non-existing edges were well explained by our model due to a significant presence of isolated municipalities.

Bridges are nodes that cover structural holes through their relationship with other nodes (De Nooy et al., 2018). The bridges usually have more control (De Nooy et al., 2018) and, in this

[1] Endogenous network statistics are dyadic-based statistics that only include connectivity information, while exogenous are covariate-based network statistics and contain information only nodal or dyadic attributes.

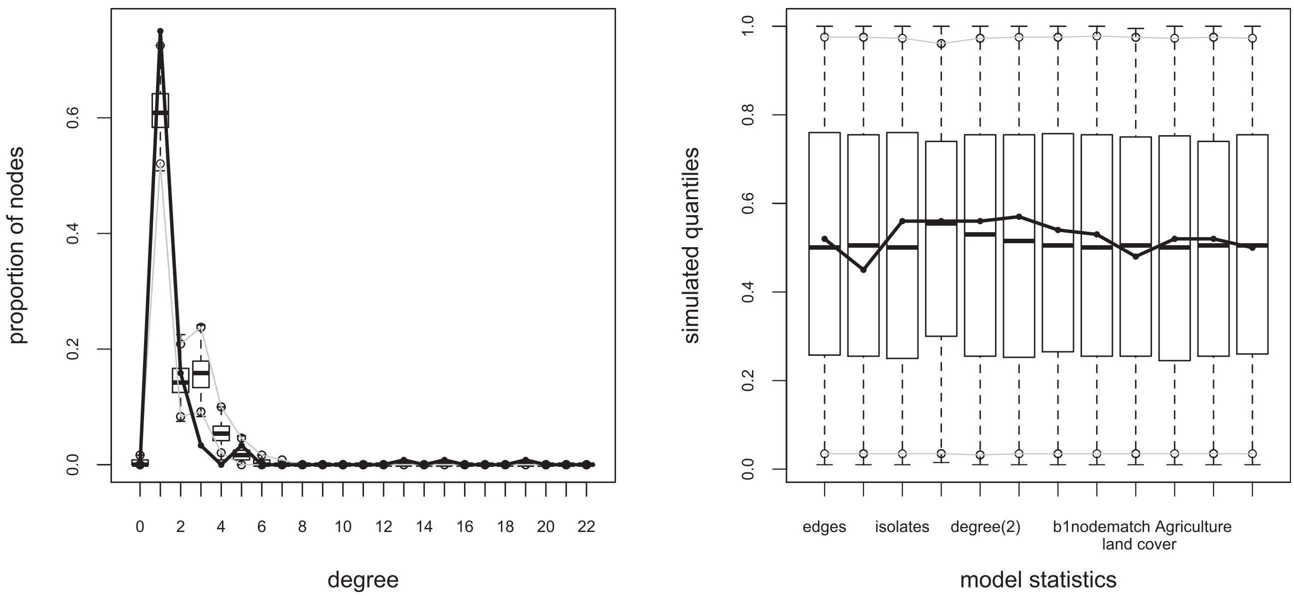


Fig. 3. Goodness of fit diagnostics of the second model including endogenous statistics. *edges, isolates, degree(2)* and *b1nodematch Agriculture land cover* are explained in Tables 3 and 4

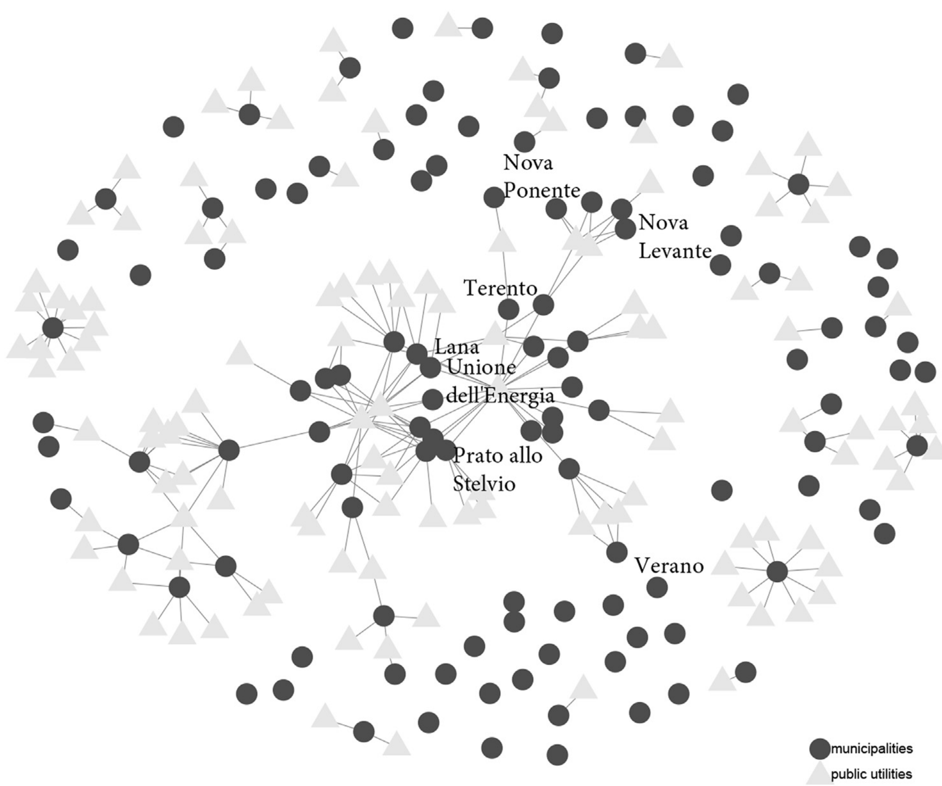


Fig. 4. The representation of the network shows several bridges, i.e., Unione dell'Energia. Considering an example, Unione dell'Energia is linked to Terento, Prato allo Stelvio, and Lana and is not linked to Nova Levante, Nova Ponente, and Verano.

research, may be relevant to spreading sustainable energy governance. Indeed, the main bridges work with on a regional perspective creating the link between municipalities that work on a local perspective. For this reason, the relevance of the main bridges of the network to create new relationships was investigated, calculating the probability of having new edges around the main bridges of the network. Looking at some bridges in Fig. 4 (i.e., Merano, Prato allo Stelvio, Egna, Bressanone, Unione dell'Energia, Consorzio energetico, Cooperativa energetica), some existing relationships should not exist according to the model (Fig. 5), and an investigation of the conditions of their existence may promote a change towards wider energy governance.

As an example, Unione dell'Energia is a bridge that might spread energy governance practices. The relationships that exist among

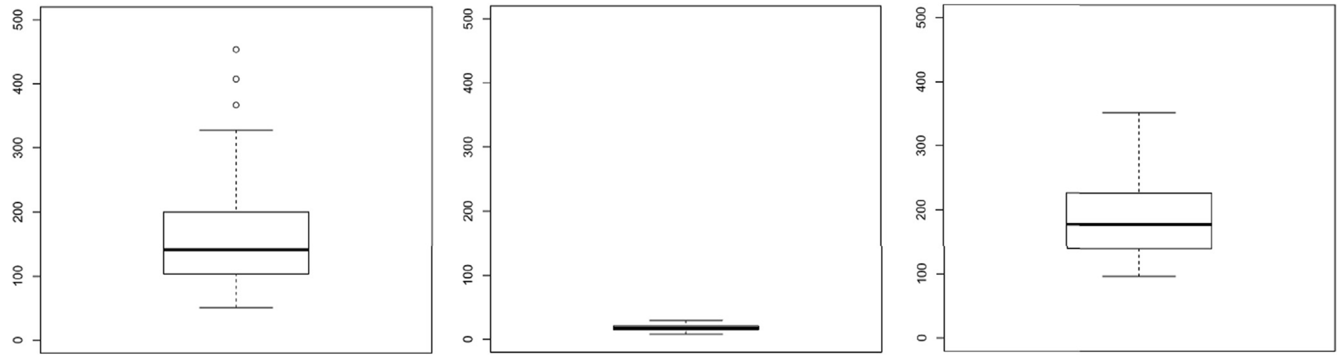


Fig. 5. The boxplots represent the probability odds to observe three edges that already exist between Unione dell'Energia (PU) and the municipalities of Terento (graph on the left), Prato allo Stelvio (graph in the middle), and Lana (graph on the right). Where values are higher than 20, the change from the existent edge to the non-existent edge is significantly likely.

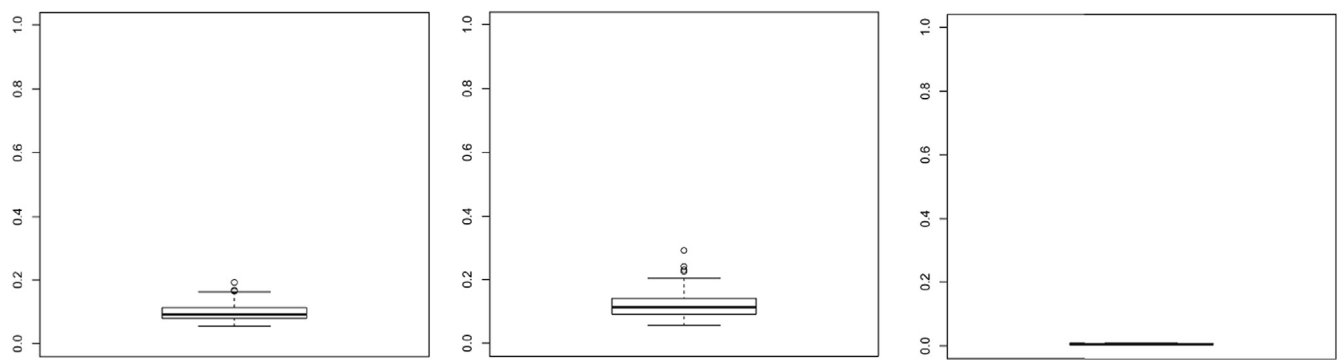


Fig. 6. The boxplots represent the probability odds to observe the three edges that do not actually exist between Unione dell'Energia (PU) and the municipalities of Nova Levante (graph on the left), Nova ponente (graph in the middle), and Verano (graph on the right). Where values are lower than 0.05, the creation of new edges in those dyads is very low.

Unione dell'Energia and Terento, Prato allo Stelvio, and Lana have a low probability of being observed (Fig. 6), but they still exist. The dynamics beyond these relationships should be deeply investigated (also through qualitative research) looking for dynamics that drive the change. Some relationships that currently exist have a low probability of being observed according to the model's estimates. These relationships are interesting because they could involve the conditions for change that the model could not explain.

Summing up, the network will probably change by reducing the number of edges (Fig. 5), but without introducing new ones (Fig. 6). For supporting some changes in relationships and for spreading sustainable energy districts, other dynamics and practices should be introduced. The model recognized that today the practice of collaborating with neighbouring municipalities and the practice to govern locally based on common solar radiation are relevant in the energy governance network. However, they are still not enough to stimulate the spread of the energy governance in South Tyrol through new edges created by the bridges.

4. Conclusions

The model investigated the existence and the opportunities to spread sustainable energy governance by analysing a network of actors and relationships within South Tyrol through a case study. In particular, the part of the energy governance composed of municipalities and PUs that practice sustainable energy governance, local planning and management of territorial resources, collaboration with other actors that have equal and similar resources and needs were investigated. This network of actors and relationships was investigated thanks to a Bayesian network model for bipartite graphs in order to underline the relational dynamics and structures that created the actual network.

The network of relationships between all 116 municipalities and 120 PUs confirms that energy governance has spread only to half the municipalities in South Tyrol and, where these kinds of relationships are observed, the network is based on relations between spatially close municipalities. Further, municipalities collaborate when they share common solar radiation resources useful to produce photovoltaic or solar thermal energy, while they prefer to individually manage the other available energy resources with the support of an individual public utility. Given the confirmed practices of collaboration based on the Bayesian exponential random graph model, the likelihood to create new relationships between municipalities and PUs is low. If policy-makers aim to further spread the energy governance practice to other municipalities, they should look at other dynamics that are not included in this networking model.

This research was the first application of a social network analysis approach with the aim to model sustainable energy districts. The flexible Bayesian exponential random graph modelling framework, which integrates data about informal relationships between municipalities in the energy sector, could be adapted to deal with several extensions. For example, relational data about the informal relationships could be collected through qualitative methods. This would provide the opportunity to integrate quantitative and qualitative methods by including one-mode network inferences based on network effects that describe the informal relational structure between municipalities, as well as the two-mode relationships between municipalities and public utilities analysed in this work.

The procedure and the open data are published in a GitLab repository with the aim of possibly replicating this analysis in other case studies and compare different results.

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