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THE IMPACT OF TECHNOLOGICAL INNOVATION SYSTEMS ON TECHNOLOGICAL VARIETY:

THE CASE OF BIOMASS DIGESTION

Master Thesis (45 ECTS)

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ABSTRACT

The technological innovation system (TIS) looks at the development and interaction of a technology with its embedded innovation system. Further, for successful technology development it is important to create technological variety. The combination of these theories is lacking in innovation literature, the aim of this study is therefore to empirically examine the influence of TIS on technological variety. Theorizing from evolutionary economics, TIS and social network analysis it is hypothesized that four concepts within these theories influence technological variety, i.e. subsidies, networks, actors and resources. These hypotheses are analyzed by assessing their influence on the technological variety of biomass digestion. This is done by fitting a multiple linear regression model to the biomass digestion projects that started during 2001-2013. In this model the technological variety of each project is measured and compared to the subsidy type, the place in the network, the number and diversity of actors and the resource diversity of the project. By performing this study it is demonstrated among others how TIS can be combined with actual technology development through the creation of technological variety. Furthermore, it is supported that research subsidies stimulate technological variety more than exploitation subsidies. Finally, the model can be used as a short subsidy evaluation tool in terms of creating technological variety.

1. INTRODUCTION

Climate change and the dependency on fossil fuels are well established problems in society. Climate change is a consequence of the CO_2 emissions (Rockström et al., 2009). The dependency on fossil fuels is a problem due to the decline in fossil fuel reserves and the political unrest in countries that have access to these resources. In order to address these problems the European Union set an ambitious target to have a share of 14% sustainable energy in 2020 (Ministry of Economic Affairs, 2011).

Biomass digestion is one of multiple technologies that produce sustainable energy. The technology is very promising because it has a multitude of potential energy sources (Markard, Stadelmann, & Truffer, 2009; Negro, Hekkert, & Smits, 2007). It produces biogas (a mixture of carbon dioxide and methane) from organic material in an oxygen-free environment, therefore it is a very useful process for waste disposal and energy production (Raven, 2004). This biogas is used to generate electricity, heat and green gas via secondary conversion technologies (Negro et al., 2007). The production of electricity is done in a cogeneration unit and has a subordinate in the form of heat (Ministry of Economic Affairs, 2010). Green gas is upgraded biogas, which can be done by various techniques and increases the methane level of the biogas to 88-95% (GroengasNL, 2012). Biomass digestion can play a large role in the production of sustainable energy (Negro et al., 2007). However, previous studies have shown that from 1970 to 2004 the technology development was problematic (Negro et al., 2007; Raven, 2004).

There are various theories of scientific literature that address technology development. First, Dosi (1982) made a distinction between technological paradigms and trajectories. The technological paradigm is the starting point of the technology and the technological trajectory is the direction in which the development changes (Dosi, 1982). Next, evolutionary economics were developed by Nelson and Winter (1982). They studied the processes that transform firms, institutions or technologies. It established two core concepts that are closely related to the technological trajectory concept of Dosi (1982), specifically variety and selection. Variety refers to the possibilities that can change a technology and selection gives direction to this variety by favoring some opportunities over others (Rigby & Essletzbichler, 1997). Thus, for technology development it is first important to create technological variety.

Another theory of innovation is the innovation system, which is first defined by Carlsson & Stankiewicz (1991, p. 94) as: "a network of agents interacting in the economic/industrial area under a particular institutional infrastructure … and involved in the generation, diffusion and utilization of technology". Within the innovation systems framework one approach specifically focuses on the innovation system around one technology. This approach is the technological innovation system (TIS) and looks at the interaction of a technology with its embedded innovation system (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007).

Three essential concepts are defined in this embedded innovation system, i.e. institutions, networks and actors (Carlsson & Stankiewicz, 1991). First, institutions are the structures that promote stable patterns of social interactions and are classified as formal and informal institutions (North, 1990). Formal institutions are crucial to economic productivity and change faster than informal institutions (North, 1994; Williamson, 1998). The formal institutions of interest for this study are the research and exploitation subsidies that stimulate the technology development of biomass digestion. They are a form of government institutions and stimulate research, development and diffusion which are important aspects of innovation (Godin, 2006). Second, networks are an intermediate form of organization between hierarchies and markets (Carlsson & Stankiewicz, 1991). Third, actors are the different agents involved in the generation, diffusion and utilization of the technology and they use networks to share, develop and exchange key resources for innovative development (Markard et al., 2009). Thus, these resources are also an important concept that influences technological variety.

The above mentioned theories of literature show complementary analytical frameworks. Where, the evolutionary economics framework looks at the evolution of a technology and the TIS framework looks at the system in which the technology is embedded. Both theories have been developed thoroughly, however the combination between these theories is lacking, because TIS scholars do not focus enough on the actual technology when explaining TIS development (Suurs, 2009). Further, a combination of these theories is valuable as technologies and innovation systems co-evolve. Consequently this study examines the influence of the previously defined concepts on technological variety. The following research question is formulated:

What is the influence of government institutions, networks, actors and resources within the technological innovation system on the technological variety of biomass digestion in the Netherlands?

Within the past ten years there have been various institutional changes in the Netherlands that were concerned with biomass digestion and the amount of biomass digestion projects in the Netherlands increased. Theoretically, this setting makes it interesting to research the influence of the previously defined concepts on the technological variety of biomass digestion within the

Netherlands. Furthermore, the TIS and evolutionary economic literature is enriched by the results of this study, as it illuminates how the TIS concepts influence technological variety. Practically, this study is particularly interesting to policy makers. It displays how institutions can influence technological variety, which helps policy makers in promoting the development of sustainable technologies.

In section 2 the theoretical framework based on technological variety and TIS literature is elaborated. Section 3 describes the research methods and in section 4 the results are presented. Finally, section 5 and 6 are concerned with the conclusion and discussion.

2. THEORETICAL FRAMEWORK

In this section, the theoretical framework to answer the research question is developed for which the relation between the TIS concepts and technological variety is of interest. This study attempts to determine how institutions and networks, which consist of actors that exchange resources, influence technological variety. Not the causality, but the correlation of these concepts with technological variety is in question. Therefore the potential feedback loops between the TIS concepts which are slow to develop, are not explicitly addressed. Preliminary hypotheses are formulated about how these concepts are related.

This section describes the literature on technological variety and institutions. In addition, the literature on networks, actors and resources is addressed. The section ends with the conceptual model.

2.1. Technological variety

After the seminal work of Dosi (1982), innovation scholars used technological trajectories mainly as metaphors of technological evolution and not to research actual technology development (Castaldi, Roberto, & Nuvolari, 2009). At the same time, the evolutionary economic literature theory was developed by Nelson & Winter (1982). This theory focuses on the process of technological innovation and studies among others the processes that transform technologies. Key concepts for this theory are variety and selection. Variety refers to the number of different technologies and opportunities in a population of elements and selection gives direction to this variety, therefore they are crucial for innovation (Van Den Bergh, Faber, Idenburgh, & Oosterhuis, 2007). Winter (2010, p. 35) states that a population will gradually adept through the process of selection. In other words, variety is influenced by the process of selection in which some technologies or opportunities are favored over others. A certain level of variety is needed for selection to operate successfully, therefore it is first and foremost important to stimulate technological variety (Rigby & Essletzbichler, 1997).

The possible technological options of biomass digestion must be defined for the successful analysis of its technological variety (Alkemade, Frenken, Hekkert, & Schwoon, 2009; Frenken, 2006). For this study a high level of aggregation is chosen by selecting three sub-systems, i.e. energy source, production type and processing type. Within these sub-systems different categories are selected. Energy source has four options, i.e. manure, organic waste, energy crops and sewage (Markard et al., 2009). Production has two options, i.e. mono- and co-digestion. Where, mono-digestion uses one type of feedstock and co-digestion uses manure combined with another energy source, also called co-substrate. The added share of co-substrates varies between 20% and 50% (Negro & Hekkert, 2008). Finally, processing has three options, i.e. cogeneration, upgrade to green gas and direct usage.

2.2. Institutions

The TIS definition from Carlsson & Stankiewicz (1991) is based on North's (1990, p. 3) definition of institutions as: "… the rules of the game in a society". These rules are comparable to the rules in a sports game with formal written rules and informal codes of conduct (North, 1990). They structure social interaction and are called formal and informal institutions, examples are law, language, table manners and organizations (Hodgson, 2006). In general, these rules enable a specific order of things by constraining or enabling human behavior. For example traffic rules enable safe driving, but they also constrain the speed limit (Hodgson, 2006). The informal institutions are often taken for granted by economists, as they change in the order of centuries or millennia. Formal institutions change quicker and are crucial to economic productivity (North, 1994; Williamson, 1998). Therefore, this study focuses on the influence of formal institutions on technological variety.

Government institutions are a type of formal institutions. They are defined as: "the rules implemented by public authorities and governmental bodies to influence market activity and the behavior of actors in the economy" (Blind, 2010, p. 219). The government can influence technological variety through the implementation of subsidies in different stages of technology development. Metcalfe (1994, p. 935) states that a distinction can be made between subsidies that take innovation possibilities as given and subsidies that seek to enhance those possibilities. From this it is derived that there are two subsidy types, i.e. research and exploitation subsidies. Research subsidies seek to enhance innovation possibilities by stimulating the research and development of a technology. Exploitation subsidies take innovation possibilities as given and try to stimulate the diffusion of a technology within these innovation possibilities. It is thus expected that research subsidies have more influence on technological variety than exploitation subsidies.

In the Netherlands there are various subsidy programs. Therefore the goals of all the subsidy programs that influence biomass digestion are analyzed, in order to determine to what category they belong, see Appendix A (NL Agency, 2012). The following hypothesis is formulated:

H1. Research subsidies are more likely to be positively associated with technological variety than exploitation subsidies.

2.3. Networks

Networks are created by actors to exchange necessary resources (Hagedoorn & Duysters, 2002; Powell & Grodall, 2005; Powell, Koput, & Smith-Doerr, 1996). They stimulate the process of experimentation and interactive learning, the exchange of knowledge and thus the development of new ideas (Caniëls & Romijn, 2008; Carlsson & Stankiewicz, 1991; Edquist & Johnson, 1997; Jacobsson & Bergek, 2004; Lundvall, 1992; Powell et al., 1996).

Wasserman & Faust (1994, p. 20) state that: "networks consist of a finite set or sets of actors and the relation or relations defined on them". These relations between actors, also called ties, can be weak or strong. A strong tie is a relationship between close friends and a weak tie is a relationship between acquaintances, it is argued that the knowledge flow on weak ties is more novel than on strong ties (Granovetter, 1973). The strength of a tie can be determined by analyzing the time, intensity and intimacy of the tie (Granovetter, 1973). Therefore, within this study the strength of ties is not analyzed, because this intensity and intimacy are unknown.

Furthermore, a network with one entity set is called a one-mode network, while a network with two entity sets is called a two-mode network (Wasserman & Faust, 1994). For this study a two-mode network is analyzed, because two sets of entities are analyzed, namely the actors and the projects in which the actors reside. This type of two-mode network is called an affiliation network, where one set of entities (actors) is measured with respect to their affiliation with a set of events (projects) (Wasserman & Faust, 1994). In an affiliation network the ties between the projects are based upon the linkages between the actors. Thus, in this study the created networks between projects through actors and not between individual actors will be analyzed.

2.3.1. NETWORK STRUCTURAL PROPERTIES

Within innovation studies centrality and structural holes are important structural properties of a network (Haynie, 2001). Centrality determines how well connected or active a project is in a network (Powell et al., 1996). For this study two types of centrality are distinguished, i.e. degree and betweenness (Freeman, 1979). Degree centrality is the number of direct ties of a project and it determines how well a project can catch the knowledge flow within the network, because more ties between projects are more likely to get access to knowledge (Caniëls & Romijn, 2008). Betweenness centrality is the frequency that a project is located on the shortest path between all possible pairs in the network (Freeman, 1979). Further, it is assumed that the knowledge distribution between projects flows across the shortest path possible. Thus by analyzing if a project is located on such a path it is possible to determine the chance that a project gets access to knowledge. Rigby & Essletzbichler (1997, p. 270) state that: "variety is generated as firms acquire knowledge about technology … through innovation and learning". In other words, access to knowledge increases the chance to create technological variety. The following hypotheses are formulated:

H2. Network degree is positively associated with technological variety.

H3. Network betweenness is positively associated with technological variety.

A structural hole is a non-redundant connection between two projects (Burt, 1995). In other words, the connection between two projects is of importance for the network. Thereby, a non-redundant connection between projects creates a connection between two different groups. Burt (2004, p. 349) argues that: "opinion and behavior are more homogeneous within than between groups". Projects connected across groups therefore have access to different sets of knowledge and they are more likely to generate new ideas. In turn, the connectivity across groups is determined by evaluating how well the neighbors of a project are connected to each other. This is called the transitivity of a project and it determines the ability of a project to create new ideas and thus create technological variety (Wasserman & Faust, 1994). The following hypothesis is formulated:

H4. Network transitivity is positively associated with technological variety.

2.3.2. Actors

North (1990) defines actors as: "the players of the game" and examples of actors are enterprises, knowledge institutes, governmental bodies and intermediate organizations (Jacobsson & Bergek, 2004; Musiolik & Markard, 2011). These different types of actors work together but do not have to share the same goals. For instance, entrepreneurs operate from an economic perspective, knowledge institutes focus on research and development, governmental bodies enforce and set policies and intermediate organizations stimulate network creation. Due to these different goals each actor has different competences and knowledge sets. By combining different actors within a project, a more unique knowledge set is created which leads to more technological variety. Also, an increase in number of actors within a project should result in more knowledge and thus more technological variety. The following hypotheses are formulated:

H5. Number of actors is positively associated with technological variety.

H6. Actor diversity is positively associated with technological variety.

2.3.3. Resources

In turn, projects collaborate with each other in order to acquire resources that cannot be generated internally, because acquiring external resources improves the sustained competitive advantage of a project (Barney, 1991; Pfeffer & Salancik, 2003). These resources are defined by Eisenhardt & Martin (2000, p. 1106) as: "physical, human and organizational assets that can be used to implement value-creating strategies". Physical capital resources include the technologies, equipment, location and raw materials. Human capital resources include the experience, judgment, intelligence, relationships and insights of the employees. Organizational capital resources include the planning, controlling and coordination systems of a project (Barney, 1991). A project with higher resource diversity has more chance to create a sustained competitive advantage by stimulating technological variety, because it is more difficult for other projects to duplicate the advantage (Barney, 1991). It may therefore be of interest for projects to stimulate resource diversity in order to promote technological variety. The following hypothesis is formulated:

H7. Resource diversity is positively associated with technological variety.

2.4. Conceptual model

The influence of the previously defined concepts on technological variety is shown in the subsequent conceptual model. Hypothesis 1 shows the relation between institutions and technological variety. Hypotheses 2-4 show the relation between networks and technological variety. Hypotheses 5 and 6 show the relation between actors and technological variety and hypothesis 7 shows the relation between resources and technological variety.

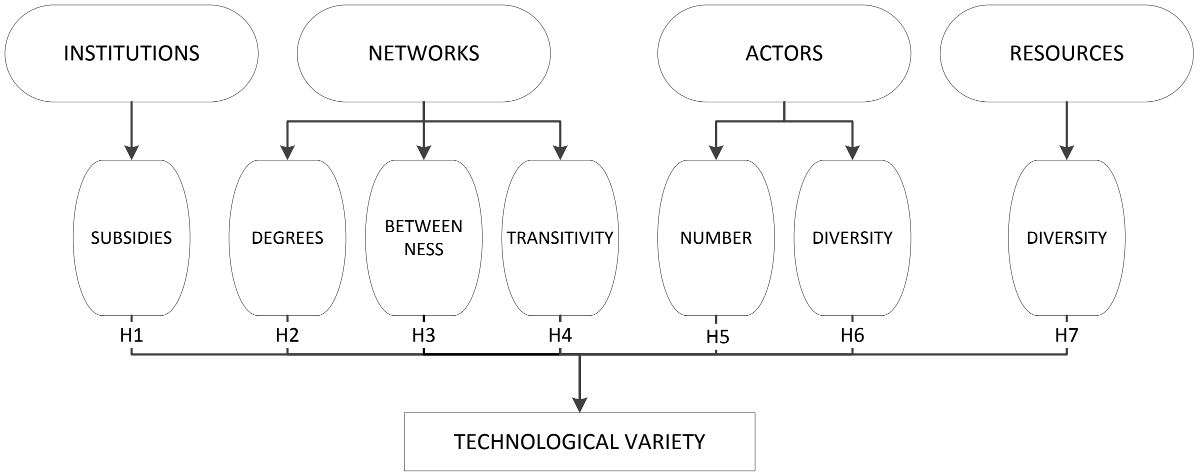

Figure 1. Conceptual model

3. RESEARCH METHODS

3.1. Empirical case and data collection

The data was collected from four different databases at NL Agency. NL Agency is an executive and counseling office of the Dutch Ministry of Economic Affairs, Agriculture and Innovation. Their databases hold information about more than 40 policy plans, 1800 energy innovation projects and hundreds of policy activities to monitor the impact of policy on different sustainable innovation systems. Furthermore, they contain information about actors and resources that are involved in sustainable innovation projects. The technological focus of these projects is also defined.

This made it possible to select all the projects that are concerned with biomass digestion from these databases. Currently, there are 406 projects concerned with biomass digestion located in these databases. It is assumed that these are all the relevant biomass digestion projects in the Netherlands, because subsidies account for 60% of their profits (Organic Waste Systems NV, 2011). The technological variety and resource diversity could be calculated for 375 of these 406 projects, of these 375 projects, 82 received a research subsidy and 293 received an exploitation subsidy.

Further, these databases hold reliable data as it is non-responsive and checked on separate occasions by employees from NL Agency, project managers and external organizations. To find additional actor information, the data was augmented with information from other sources such as actor web pages, the Dutch Chamber of Commerce and project reports.

3.2. Measurement

The network in this study is an affiliation network, where the two entity sets are a set of actors and projects. Whether, two projects have a connection was measured by analyzing if the actors within the first project have ties to actors in the other project. The variables are often measured at project level, except for technological variety which is also measured at year level in order to show how it changed during the past years. This makes it possible to determine if the technology is shifting towards a single dominant design. Furthermore, the technological project variety is measured at a relative and absolute scale, because the increase in projects over the years can influence the results.

Technological year variety (H) is measured by the formula of entropy (F1), based on previous work by Theil (1972) and recent innovation studies (Bakker, 2010; Frenken, Hekkert, & Godfroij, 2004; Frenken, Saviotti, & Trommetter, 1999).

$$H = \left(-\left(\sum_{i=1}^{n} p_i \cdot \ln p_i\right)\right) \quad \text{(F1)}$$

Where p_i is the share of an option within sub-system *I* and n is the total number of available options in sub-system *i*. The technological variety is different per sub-system, because it is dependent on the amount of possible options. Therefore, the value is divided by the maximum technological variety, which is calculated by the following formula (F2):

$$H_{max} = -1 * \ln\left(\frac{1}{n}\right) \tag{F2}$$

This gives a value between 0 (no technological variety) and 1 (perfect technological variety) for every sub-system, which makes it possible to compare the different technological varieties and to calculate an average technological variety.

The *relative technological variety* (V_{rel}) is calculated by the following formula (F3):

$$V_{rel} = 1 - \left(\left(\frac{\left(\frac{\sum_{i=1}^{n} p_i}{\sum_{i=1}^{n} i}\right)}{i_{max}}\right) + \left(\frac{\left(\frac{\sum_{j=1}^{n} p_j}{\sum_{j=1}^{n} j}\right)}{j_{max}}\right) + \left(\frac{\left(\frac{\sum_{i=1}^{n} p_k}{\sum_{i=1}^{n} k}\right)}{k_{max}}\right)\right) \tag{F3}$$

Where *i* is a technological input option, *j* is a technological production option, *k* is a technological processing option, p_i, p_j & p_k are the share of each possible technical option and i_{max}, j_{max} & k_{max} are the maximum values of each option. The share of each option is divided by the amount of options that are chosen and afterwards divided by the maximum amount of each type. The different variation types are added together and subtracted from 1, again in order to achieve a value between 0 and 1. From the data it was found that the average relative technological variety for exploitation projects $(V_{rel}(exp))$ is 0.32 with a SD of 0.36. The average relative technological variety for research projects $(V_{rel}(res))$ is 0.49 with a SD of 0.34, which implies that research projects create more technological variety than exploitation projects.

The *absolute technological variety* (V_{abs}) is calculated by the following formula (F4):

$$V_{abs} = -1 * \ln\left(\left(\left(\frac{\sum_{i=1}^{n} m_i}{\sum_{i=1}^{n} i}\right)\right) + \left(\frac{\sum_{j=1}^{n} m_j}{\sum_{j=1}^{n} j}\right) + \left(\frac{\sum_{i=1}^{n} m_k}{\sum_{i=1}^{n} k}\right)\right) \tag{F4}$$

With four differences compared to the previous formula (F3). First, m_i, m_j & m_k represent the absolute values that each possible option is chosen. Second, the natural logarithm is taken because the absolute values were very high and third, the natural logarithm is multiplied by -1 in order to achieve that a higher number represents increasing technological variety. Also, the values were not divided by the maximum technological variety for each option, because it is dependent on the total number of chosen options, which changed constantly. From the data it was found that the average absolute technological variety for exploitation projects $(V_{abs}(exp))$ is -14.25 with a SD of 2.40. The average absolute technological variety for research projects $(V_{abs}(res))$ is -10.87 with a SD of 3.46. Again, this implies that research projects create more technological variety than exploitation projects.

Network project degree (D) is measured by calculating the amount of ties that a project's actors have with actors from other projects (Caniëls & Romijn, 2008). The average network project degree (D_{avg}) is 3.11 with a SD of 2.00, thus a project has on average three ties through its actors with other projects. When only the research projects are taken into account then the average network project degree $(D_{avg}(res))$ is 4.27 with a SD of 2.91.

Network project betweenness (B) is measured by calculating the frequency that a project is located on the shortest path between all possible pairs of projects in the network, which Wasserman & Faust (1994) call a geodesic. See the following formula (F5) (Freeman, 1977):

$$B(i) = \sum_{j \neq i \neq k} \frac{g_{jk}(i)}{g_{jk}} \quad \text{(F5)}$$

Where g_{jk} represents the number of geodesics between project *j* and *k* and $g_{jk}(i)$ represents the number of geodesics between project *j* and *k* that contain actor *i*. This formula considers the probability that the knowledge flow between project j and k takes a particular route passing project i. The average network project betweenness (B_{avg}) is 0.98 with a standard deviation of 6.36.

Network project transitivity (T) is measured by determining if there is a triad relation between three projects. Wasserman & Faust (1994, p. 150) define a transitive relation: "whenever i -> j and j -> k then i -> k, for all projects i, j en k". It determines how well the neighbors from project i are connected to each other, where higher transitivity means more connected neighbors. The average network project transitivity (T_{avg}) is 0.19 with a SD of 0.38, thus neighbors are often not connected. When only research projects are taken into account then the average network project transitivity (T_{avg}) is 0.38 with a SD of 0.46.

Actors are classified according to the guideline from the European Commission (2005). A firm with less than 250 employees is classified as a small-medium enterprise (SME) and a firm with 250 or more employees is classified as a large enterprise (LE). Universities and research institutes are classified as knowledge institutes (KI) and governmental organizations are classified as governmental bodies (GB). Actors that focus on bringing together a group of actors are classified as Intermediary

Organizations (IO).There are 401 unique actors located in the database of which 71% were labeled SME, 12% were LE, 7% were GB, 6% were IO and 4% were KI.

Number of actors (N) is the sum of actors that are part of a project. The average number of actors per project (N_{avg}) is 1.56 with a SD of 1.47. This value is influenced by the exploitation projects for which only one actor is known, thus of interest is the average number of actors for research projects which is 3.59 with a SD of 2.12.

Actor diversity (A) is also calculated by using formula F1, where the possible options are the five previously defined actor types: SME, LE, KI, GB and IO. The average actor diversity is 0.11 per project but this is influenced by the exploitation projects for which only one actor is known. Thus the average actor diversity for research projects (A_{avg}) is 0.52 with a SD of 0.42 and the maximum actor diversity (A_{max}) is 1.61.

Resources are categorized according to the literature as: physical, human and organizational. However, within the databases of NL Agency the resources are further classified in sub-categories. This categorization is also used in this study by sorting dummy variables under the three resource types found in the literature, see table 1.

Table 1. The resources dummies sorted under the three resource types from the literature

Literature categorization:	**Physical**	**Human**	**Organizational**
Dummy variables:	Capital	Knowledge technology	Manpower
	Feedstock	Knowledge market	Network
	Instruments: technology	Knowledge law	
	Instruments: equipment		
	Licences		
	Location: ground		
	Location: building		
	Location: research facility		
	Patents		

Resource project diversity (R) is also calculated by using formula F1, where the possible options are the in table 1 defined dummy variables. There are 82 possible observations for resource diversity, because the resources are not known for the exploitation projects. The average resource diversity (R_{avg}) is 1.51 with a SD of 0.53 and the maximum resource diversity (R_{max}) is 2.64.

Institutions are measured by determining which subsidy a project received. There are different subsidy programs which are categorized between research and exploitation subsidies. The research subsidy programs within this study are: DEN (Duurzame Energie Nederland), EOS (Energie Onderzoek Subsidie), IAE (Innovatie Agenda Energie), ROB (Reductie Overige Broeikasgassen) and

UKR (Unieke Kansen Regeling). Next, the exploitation subsidy programs within this study are: MEP (Milieukwaliteit ElektriciteitsProductie), OVMEP (OVergangs Milieukwaliteit ElektriciteitsProductie) and SDE (Subsidie Duurzame Energie). There were 82 research projects analyzed, subdivided in 29 DEN-projects, 23 EOS-projects, 15 ROB-projects, 14 IAE-projects and 1 UKR-projects. In turn, there were 293 exploitation projects analyzed, subdivided in 137 SDE-projects, 96 MEP-projects and 60 OVMEP-projects.

The *subsidy type* (S) is thus measured by determining if a project received a research or exploitation subsidy.

Year (Y) is determined by the year in which the project received subsidy. This continuous variable ranged from 2001 to 2013.

3.3. Analysis

The dependent variable is technological variety (V). The independent variables are year (Y), network degree (D), network betweenness (B), network transitivity (T), number of actors (N), actor diversity (A), resource diversity (R) and subsidy type (S). This gives the following model:

$$V = \beta_0 + \beta_Y Y + \beta_D D + \beta_B B + \beta_T T + \beta_N N + \beta_A A + \beta_R R + \beta_S S + \varepsilon$$

Where β_0 is the model intercept, the other β's represent the regression coefficients for the predictor variables and ε is the difference between the predicted and the observed value of technological variety.

Based on this model the hypotheses were tested by fitting a multiple linear regression model to the data, for which the adjusted R^2 and the corresponding β's were calculated. The model was fitted for all projects together and research projects separately. Hypothesis 1 was tested in the model for all projects, while the other hypotheses were tested in the model for research projects. The variable year could not be used as a categorized control variable because the amounts of observations per year were too small. Therefore, it is used as a predictor variable.

4. RESULTS

Before addressing the statistical results, two graphs are presented to give a general sense of what happened with the biomass digestion technology from 2001 until 2013.

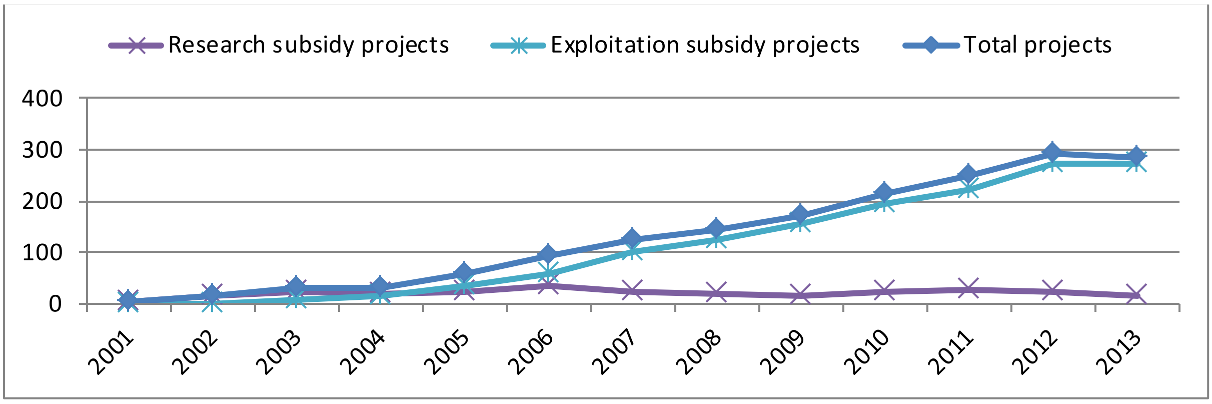

Figure 2. Number of projects per year

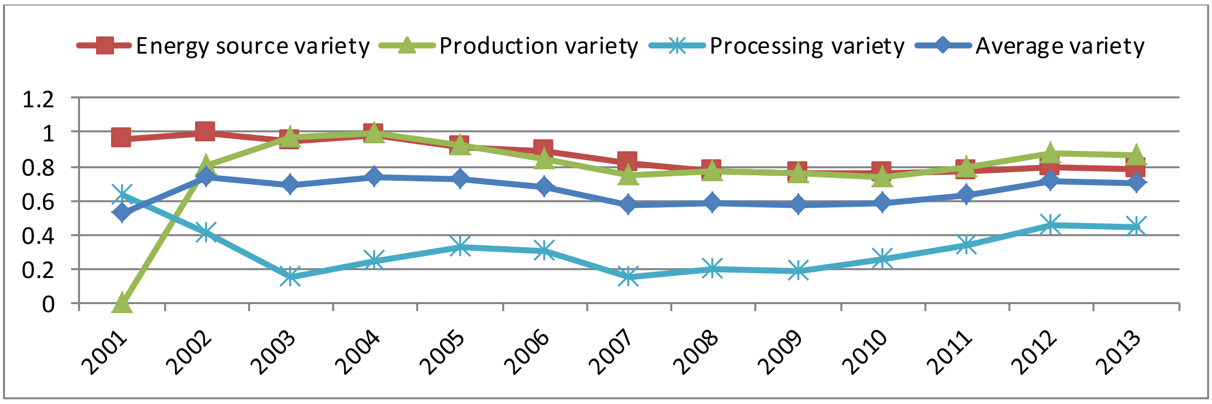

Figure 3. Energy source, production and processing variety per year

Figure 2 shows the number of biomass digestion projects and figure 3 shows the technological variety per year for energy source, production and processing. The number of projects between 2001 and 2004 were very low, which is in line with previous studies on biomass digestion (Negro et al., 2007; Raven, 2004). It results in an almost perfect variety for energy source and production variety. Further, the production and processing variety changed much in the beginning. The total number of biomass digestion projects is steadily increasing, except in the year 2013 for which it is still possible to apply for a subsidy. The research projects stay fairly constant, thus the total number of projects increases mainly due to exploitation projects. This increase in exploitation projects should result in a more diffused technology. However this is not the case, since the average variety did not decrease. Furthermore, in appendix B the correlations between the entropy variety at year level and the relative and absolute project varieties are given. Where, entropy variety and relative variety are significantly correlated (0.90).

RESULTS

The energy source and production variety stay moderately constant around 0.8. Further, the processing variety is lower, but it steadily increases from 2009. The reason for this is probably the SDE subsidy program which started in 2008. This is an exploitation subsidy which stimulated green gas for the first time, which thus results in more technological processing variety.

Table 2. Multiple linear regression model results for all projects

		All projects			
		Relative variety		Absolute variety	
	Intercept (fixed)	-99.99	***	974.62	***
	Year	0.42	***	-0.49	***
Network	Degree	0.07		-0.24	***
	Betweenness	-0.10		0.03	
	Transitivity	-0.01		0.12	
Actor	Number	-0.18	*	-0.21	**
	Diversity	0.21	*	0.19	**
Subsidy	Research	**0.36**	***	**0.33**	***
	Exploitation	**-0.36**	***	**-0.33**	***
Model indicators	Adjusted R^2	0.19	***	0.48	***
	df	7		7	
	Valid N	378		378	
*: $\rho < 0.05$. **: $\rho < 0.01$. ***: $\rho < 0.001$.					

The results from the multiple linear regression models for all projects are displayed in table 2. The results show that research subsidies significantly and positively influence relative (0.36) and absolute variety (0.33). Thus, hypothesis 1 is supported by the model. Hypotheses 2 to 7 will be addressed by analyzing the model results for research projects, because they stimulate technological variety more than exploitation projects, see table 3.

Table 3. Multiple linear regression model results for research projects

		Research projects			
		Relative variety		Absolute variety	
	Intercept (fixed)	-129.51	***	1786.09	***
	Year	**0.55**	***	**-0.75**	***
Network	Degree	-0.66	**	-0.30	*
	Betweenness	0.29		0.09	
	Transitivity	0.04		0.03	
Actor	Number	-0.14		-0.27	***
	Diversity	0.32	**	0.23	***
Resource	Diversity	0.03		0.16	**
Model indicators	Adjusted R^2	0.36	***	0.77	***
	df	7		7	
	Valid N	82		82	
*: $\rho < 0.05$. **: $\rho < 0.01$. ***: $\rho < 0.001$.					

RESULTS

Hypothesis 2 is contradicted by the model, which gives a negative significant relation of network degree with relative (-0.66) and absolute variety (-0.30). Projects with more ties to other projects create less variety. The relation between network betweenness and relative or absolute variety is not significant, thus hypothesis 3 is not supported by the model. It is unknown if a project which is located on the shortest path between other projects is more likely to create variety. Also, hypothesis 4 is not supported by the model, since there is no significant relation between network transitivity and relative or absolute variety. Thus, the transitivity of projects is not of influence on the creation of variety.

Subsequently, the relation between number of actors and relative variety is not significant, but the relation between number of actors and absolute variation is significant (-0.27). However, it contradicts hypothesis 5 since it is a negative relation. This means that more actors in a project result in less variety. Further, hypothesis 6 is supported by the model. The relations between actor diversity with relative (0.32) and absolute variety (0.23) are both positively significant. Thus, a project with a more diverse set of actors is likely to create more variety. Next, hypothesis 7 is also supported by the model, since the relation between resource diversity and absolute variety is positively significant (0.16).[1] Thus, a project with a more diverse set of resources is likely to create more variety.

Both models for relative and absolute variety perform well, with a significant adjusted R^2 of 0.36 and 0.77. A reason for the better performance of absolute variety is that it is more correlated with year (appendix C). This variable has a positive significant relation with relative variety (0.55) and a negative significant relation with absolute variety (-0.75). Further, the histogram and normal P-P plot of the regression standardized residual for relative and absolute variety show a skewed distribution for relative variety and a normal distribution for absolute variety (appendix D and E). The model for absolute variety thus is a better fit than the model for relative variety. Another reason for this better fit could be the increase in projects during the past years, because it could influence the results that are achieved for absolute variety. However, only the research projects were used for the model and they did not increase over the past years, instead they vary around 20 projects.

[1] The relation between resource diversity and relative variety is not significant.

5. CONCLUSIONS AND DISCUSSION

The aim of this paper was to empirically examine the influence of TIS on technological variety. Theoretically, a combination of TIS and technological variety was proposed. Where, a combination between TIS, evolutionary economics and social network analysis theory was used to define institutions, networks, actors and resources. Further, the influences of these concepts on technological variety were researched. The proposed model performs very well in determining how the creation of technological variety was influenced by TIS.

It confirms that research subsidies stimulate technological variety more than exploitation subsidies. For successful technology development, it is therefore important to stimulate research subsidies in order to create variety. Afterwards exploitation subsidies must be stimulated in order to select within this variety, which is supported by the theory on evolutionary economics (Nelson & Winter, 1982; Rigby & Essletzbichler, 1997).

Next, it was found that a more diverse set and not the number of actors lead to more technological variety. Thus, in order to create technological variety it is important to stimulate the involvement of different actor types in a project. By creating a project it is therefore crucial to determine which actors should be involved in this project and not blindly stimulate all actors. Further, resource diversity has a positive significant relation with technological variety. Thus, if a project has a more diverse set of resources, than this is positive for the creation of technological variety.

To conclude, for the creation of technological variety it is important for a project to stimulate diversity in general. It is also important for projects to not have too many ties with other projects, because this is not positive for the creation of technological variety. Therefore, a project should stimulate the involvement of different actors and resources, while keeping an eye on its number of ties with other projects.

5.1. LIMITATIONS AND FURTHER RESEARCH

The limitations of this study and possibilities for further research are mentioned before the implications of this study are discussed. The first and main limitation of this study is that only one technology is analyzed. The sample is large enough but the results are entirely focused around one technology. Therefore, the results from this study cannot be generalized to other sustainable technologies. Future research on the influence of TIS on the development of other sustainable technologies and in other countries is necessary.

In addition, it was impossible to collect all the actors and resources for the exploitation projects. Only the actor that exploited the biomass digestion installation was known. This limitation was solved by first determining the influence of research and exploitation subsidies on technological variety. Afterwards, the model was analyzed only for research project, since the relation between research subsidies and technological variety was positively significant. The results from this study are therefore not biased by this limitation. However, future research on actors and resources within exploitation projects is necessary.

Next, it was only addressed if a project used a certain resource type and not the absolute amount that was used. It was chosen to assess the resources this way because not all the absolute amounts for each resource were known and furthermore the differences between resource types make it difficult to generalize. Therefore, only the resource diversity was addressed in this study. Future research on the influence of the absolute amounts of each resource type on variety is necessary.

Finally, there are two limitations concerned with the relations between projects, i.e. the direction and strength of these relations. The direction of the relations in this study are always two-tailed, this means that they go from project *i* to project *j* and vice versa. However, it could be possible that only one project benefits from a relationship. Furthermore, in this study the strength of the ties between projects was not taken into account, because the intensity and intimacy of these ties were unknown. However, the negative significant relation between network degree and technological variety could be explained by the strength of ties, since it is expected that weak ties stimulate technological variety more than strong ties (Granovetter, 1973). Further research could address this by defining the relations between actors in the same project as strong ties and the relations between actors in different projects as weak ties.

5.2. Theoretical implications

This study leads to three theoretical implications that contribute to innovation theory thinking. First, this study adds to innovation literature by combining TIS and technological variety, which is invaluable as innovation systems and technologies co-evolve. Innovation systems try to influence technology development by creating the ideal configuration and technological variety is the first and crucial step in this development. Previous studies have addressed these two theories together, but the direct combination was still lacking in the literature. This study shows how these two theories can be combined to assess the development of a technology in terms of technological variety. Furthermore, the literature on TIS has been improved by determining its actual influence on technological variety.

Second, this study adds to the evolutionary economic literature, by showing a crucial relation of actor and resource diversity with technological variety, since they both have a positive significant relation with technological variety. Actor diversity is also significantly correlated with resource diversity (appendix C). Hence, diversity creates variety and in order to stimulate technological variety it is important to involve different actor types in a project because they can share their different resource sets.

Finally, the results imply that projects with fewer actors and also fewer relations to other actors stimulate technological variety more. The implication that more relationships do not result in more technical variety supports the notion that it is important for actors and projects to carefully decide with whom to build a relationship. Therefore, the results from this study make it clear that more ties between actors and projects do not always result in technological variety. This is in contrast with current literature on network creation (Burt, 1995; Caniëls & Romijn, 2008). However, it is possible that an explanation for this lies with the strength of ties between projects (Granovetter, 1973).

5.3. Practical implications

The results of this study also lead to two practical implications. At first, the study shows that research subsidies increase and exploitation subsidies lower technological variety. This argument can be used in favor of subsidies, because the creation of technological variety can be achieved by developing research subsidies. Further, this technological variety can be exploited by developing exploitation subsidies, since exploitation subsidies lower technological variety through the stimulation of selection.

Second, the model can be used as a short evaluation tool of subsidy programs in terms of creating technological variety for NL Agency. The model allows determining if and how a specific subsidy program influenced the technological variety for a sustainable energy technology. This is useful for subsidy policy evaluation and can thus be used when subsidy programs for sustainable technologies are being evaluated or developed. It is important for NL Agency to take into account that there are different subsidy types which focus on different parts of technology development. Therefore when NL Agency evaluates or develops a subsidy, it should always be addressed if they want to stimulate technological variety or selection, because they are achieved differently.

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APPENDIX A. SUBSIDY PROGRAM GOALS

Subsidy programs	Goals & measures	Research	Exploitation
Duuzame Energie Nederland (DEN)	Network creation Knowledge distribution	X	
Energie Onderzoek Subsidie (EOS)	Research of new sustainable energy technologies Knowledge distribution	X	
IAE (Innovatie Agenda Energie)	Research and development of new sustainable energy technologies To learn from applying new sustainable technologies	X	
Reductie Overige Broeikasgassen (ROB)	To map cost effective emmission reduction options Knowledge distribution	X	
Unieke Kansen Regeling (UKR)	Stimulating the transition to sustainable energy Promoting market introduction of new sustainable energy technologies	X	
Milieukwaliteit Elektriciteits Productie (MEP)	Production of sustainable electricity		X
Overgang Milieukwaliteit Elektriciteits Productie (OVMEP)	Transition regulation for biomass digestion installations that produce electricity		X
Subsidie Duurzame Energie (SDE)	Production of sustainable energy: electricity, heat and green gas		X

APPENDIX B. PEARSON CORRELATION MATRIX FOR VARIETY LEVELS

	Entropy variety		Relative variety		Absolute variety	
Entropy variety	1.00					
Relative variety	0.90	**	1.00		.	
Absolute variety	0.02		-0.18		1.00	

**. Correlation is significant at the 0.01 level (2-tailed)

APPENDIX C. PEARSON CORRELATION MATRIX FOR RESEARCH PROJECTS

	Year	Network degree	Network betweenness	Network transitivity	Number of actors	Actor diversity	Resouce diversity	Relative variety	Absolute variety
Year	1.00								
Network degree	0.16	1.00	.	.	.	.	.	.	
Network betweenness	0.27 **	0.15	1.00	.	.	.	.	.	
Network transitivity	0.37 **	0.69 **	0.66 **	1.00	.	.	.	.	
Number of actors	0.33 **	0.17	0.30 **	0.41 **	1.00	.	.	.	
Actor diversity	0.26 **	0.22 *	0.19 *	0.33 **	0.67 **	1.00	.	.	
Resouce diversity	0.14	0.00	0.18	0.14	0.46 **	0.36 **	1.00	.	
Relative variety	0.43 **	-0.05	-0.20	-0.21	0.02	0.22 *	0.07	1.00	
Absolute variety	-0.82 **	-0.19	-0.31 **	-0.44 **	-0.31 **	-0.05 **	0.00	-0.01	1.00

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).

APPENDIX D. RESIDUAL DISTRIBUTION PLOTS OF RELATIVE VARIETY

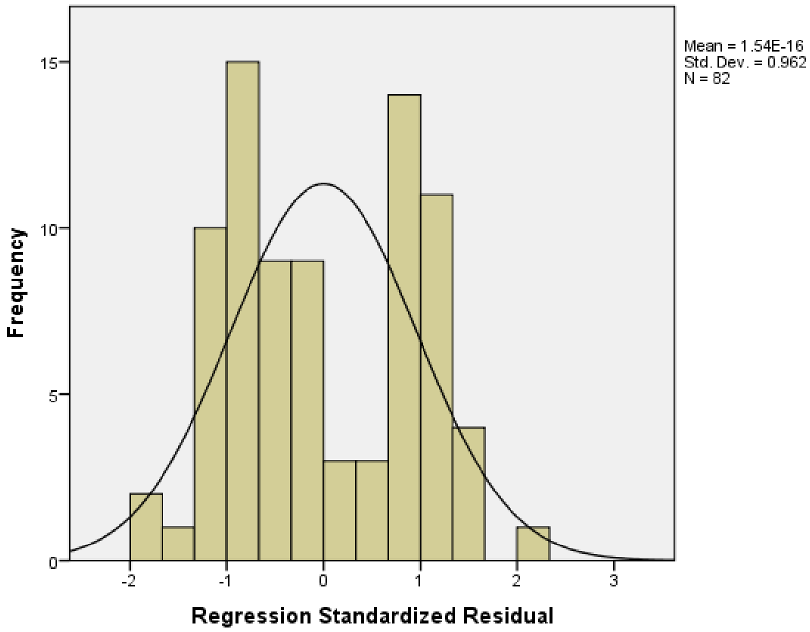

Figure 4. Histogram

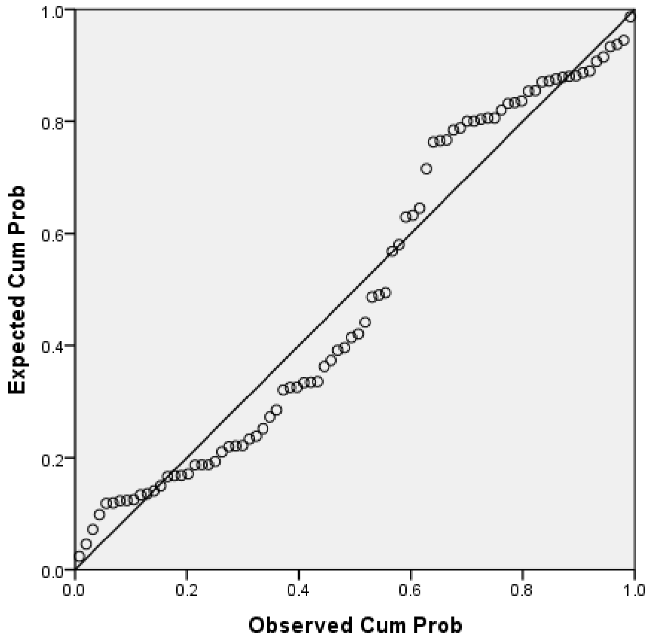

Figure 5. Normal P-P plot of non-normally distributed residuals

APPENDIX E. RESIDUAL DISTRIBUTION PLOTS OF ABSOLUTE VARIETY

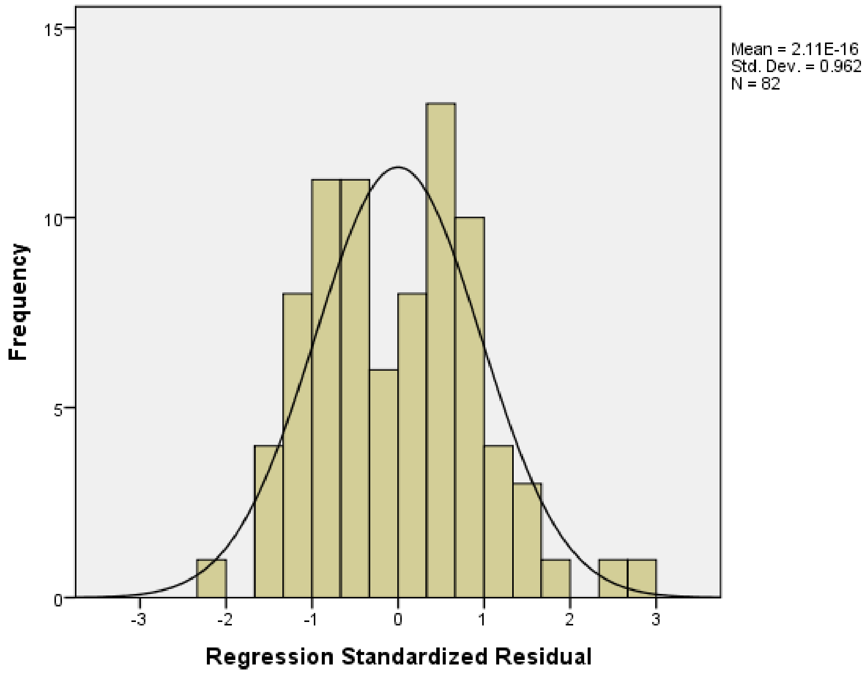

Figure 6. Histogram

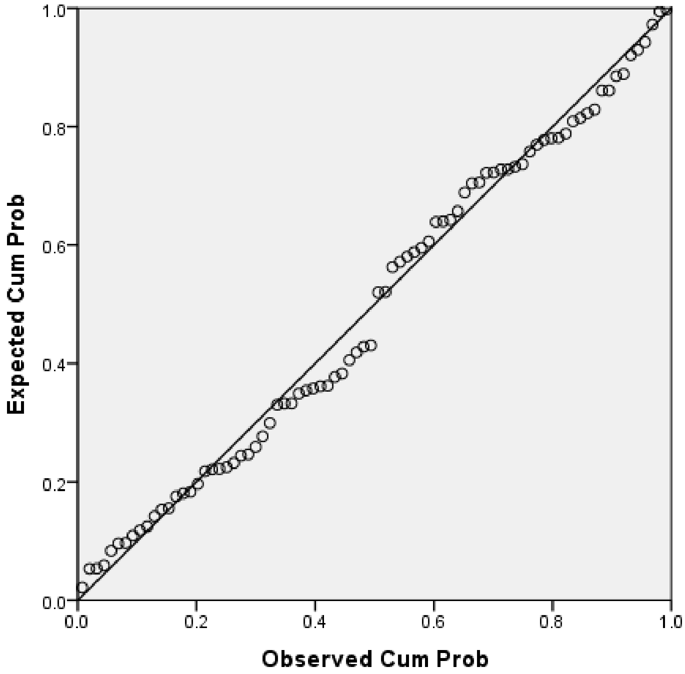

Figure 7. Normal P-P plot of normally distributed residuals