POLITECNICO DI TORINO

Master's Degree Course in Communications and Computer Networks Engineering

Master's Degree Thesis

Analysis of Energy Communities

Academic Year 2019-2020

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Abstract

With the use of smart technologies as a rising trend, the inadequacies in the fields of economy, environment, security, safety, reliability and efficiency in the traditional electricity grid have played an active role in the emergence of the idea of having a smart electricity grid. Smart Grid meets the requirements of the complex operating environment on electric power systems and gives the solutions for global energy and environmental problems which are the essential public concern of the last century. The success rate of these solutions offered by Smart Grid is directly related to the efficiency of energy distribution among the actors in the electric power grid. Since Smart Grid is a user-oriented system, user behaviours directly affect energy distribution efficiency. Therefore, analysing the behaviour of actors using different approaches and scenarios provides information to discover the most effective energy efficiency distribution for the network. In this thesis, a review of analysis on the energy grid (in Piemonte, Italy) was performed by using graph theory on complex networks to discover information about the feasibility and deployment of energetic communities that are used for smart and renewable energy systems. The existing grid structure was analysed from two different perspectives, mainly topological perspective and weighted real-like perspective. The detail of the electromagnetic process was neglected during the analysis, and abstract grid graph structures were used for the implemented perspectives. The behaviours of these perspectives have been observed using different energy distribution scenarios by applying the standard, high path failure and no path failure conditions. The results show that the feasibility and deployment of a renewable energy system on Piemonte national grid structure is highly possible with the use of existing grid features since the structure can meet with the needs of the customer-based system, distributed energy production and energetic communities. On the other hand, the results from different scenario applications indicated that the use of a consumption-based energy distribution approach is more efficient than the production-based one. Since in some cases, the large-scale producers dominate the production, the balance between actors in the grid should be improved by increasing the implementation of distributed energy production such as giving active roles also the customers as energetic communities.

Keywords: Energy Communities, Smart Grid, Microgrid, Energy-Efficient Distribution, Graph Theory

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1. Introduction

1.1. Motivation

Since the implementation and the use of Smart Technologies started to increase, the idea of applying a Smart System on traditional grids has also become a hot topic of improving energy distribution performance. Even though at the beginning, the purpose of adding smartness on the traditional grid was adjusting the energy distribution performance, now it has become more and more critical with a vast scope of substantial benefits [1]. These benefits can be divided into six areas:

- Economics: by reducing the consumer payments for the service with the usage of an energy-efficient distribution, increasing financial benefits of production, new job opportunities.
- Efficiency: by decreasing the cost of production, electricity consumption and electricity transfer.
- Environmental: by increasing the usage of renewables and reducing greenhouse gas emission.
- Reliability: by reducing the probability of transmission failures in the system and power outage prevention.
- Safety: by creating a safe, smart grid to reduce grid-related injuries.
- Security: by reducing the probability of system attacks and natural disasters.

In 2007, three crucial key targets (20/20/20 targets), meaning 20% reduction in GHG (Greenhouse Gas) emission, 20% of EU energy production from Renewables, and 20% advancement in Energy Efficiency, were described and they were legislated in 2009 by EU leaders. Also, the 2020 Climate and Energy Package (Europe 2020 Strategy Plan) has headlined these key targets to achieve the goal of smart, sustainable and inclusive growth [2].

To meet the key targets, transforming the traditional grid structure to a smart and more effective grid, called Smart Grid, became very critical. In Smart Grid, the system provides a user-oriented service aiming at a cost-effective energy-efficient distribution [3]. Smart Grid as a concept is a self-sustained grid that has users with different characteristics (consumer, prosumer and producer) connected to the system. Improving the energy distribution efficiency by also considering the cost effectivity is strongly related to the proper implementation of Smart Grid by analysing the behaviour and actions of all users. The data collected by smart meters (mentioned in section 2.2.1.) in the grid are used to analyse the behaviour and actions of actors to achieve a better grid performance. Since the purpose of the analysis is to provide information about the actor behaviours in the system, it is vital to analyse the performance metrics of the energy distribution both from consumption and production sides.

1.2. Thesis Objectives & Research Questions

Given the information in Section 1.1, it is essential to know consumption needs and production levels to relate the actions of actors in energy communities to create a self-sustained grid structure. Unlike from the traditional grid system, customers are highly active in smart grids, and they have the critical roles in the performance of the system since with the use of smart technologies, consumers can sell, buy, control their energy consumptions or even they permit it to be controlled [4].

This work aims to make elucidator inferences about the adoption and feasibility of energetic communities to meet with the requirements of dynamic self-sustainable energy systems with the use of renewables referred in the EU Clean Energy For All Europeans Package. The analysis was performed with the implementation of graph theory to represent a complex grid network in the Piemonte Region of Italy. In the case study, two different graph representation approaches were implemented; (1) the topological approach (by considering the topological connections between nodes – distance parameter between nodes is hop counts) and (2) the real-like approach (distance parameter between nodes is real distance measure in meters). In both approaches, the electromagnetic features of the grid were neglected. There are two scenarios implemented on each approach; a consumption-based and a production-based scenario. Each scenario applied under the two-constraint strategy; (a) distribution of 70% of available energy per producer and (b) distribution of available energy without any constraint. All scenarios were analysed for three different cases; standard case - a conventional energy distribution system, high failure case - an energy distribution system with high path failure probability, and no failure case - an energy distribution system with zero failure. All results were collected from the analysis for three days of a week, Monday, Wednesday and Sunday to observe the grid behaviours under different cases both from the consumer-oriented and producer-oriented point of view with both topologically and real-like approaches.

Data collecting from real grid actors in the Piemonte Region of Italy were used during the analysis to implement the approaches above. Besides, the answers to the following research questions were tried to be found in the analysis:

Research Question 1:
What are the benefits of energetic communities and smart renewable production systems in a grid? The answer will give a better understanding of the energy community concept.

Research Question 2:
What are the characteristics of the energy distribution system actors in the grid? The answer will give a better understanding of the actors and their actions in Piemonte to measure the feasibility and deployment features of energetic community concepts on real energy distribution structure.

Research Question 3:
What is the behaviour of Pieomente energy distribution system under different cases, constraints and conditions? The answer will present better implementation and adaptation solutions of the energy distribution system for real grid structure.

Research Question 4:
How should the feasibility and deployment of energy communities be in Piemonte region considering the energy efficiency of the distribution system? The answer will point out the strategies that can be used to improve an energy-efficient distribution system in the region according to results from different strategies.

1.3. Thesis organisation

Chapter 2 will give a brief explanation about Smart Grid Technologies & Smart Metering, Micro-Grid Systems, the concept of energetic communities to achieve clarity about the concept of smart renewable energy systems. Also, a brief description of the technologies and tools used for the analysis will be included in this section.

Chapter 3 will introduce the policies, projects and studies about the concept of energetic communities and smart system implementations to catch the functionalities of future energy distribution structures. This section provides a clear explanation to answer Research Question 1.

Chapter 4 will explain the methodology followed during the analysis. This section includes a brief explanation about the dataset (where all data collected from the grid, in Piemonte Region, stored and were used in the analysis), the representation of the energy grid by using the graph theory and node characteristics. It also answers Research Question 2 & 3, and a brief description of the scenarios implemented to the analysis, calculation of the path reliabilities and the energy distribution algorithms that were used in the analysis.

Chapter 5 will explore the information used in chapter 4, and it will find answers to Research Question 4.

Chapter 6 will conclude the thesis in light of the information obtained from the above chapters, and it will also propose future works and implementations by considering the results acquired from the analysis.

2. Background

2.1. From Traditional to Smart Grids

The electric grid (power grid) is an electrical network system based on the concepts of generation, transmission and distribution, which includes a large number of complex connections between energy customers (consumers and manufacturers). In this thesis paper, there are two different concepts of grids mentioned: Traditional Power Grid and Smart Grid. The history of Traditional Power Grid begins with the first installation by using a centralised unidirectional power distribution in Great Barrington, Massachusetts in 1886 and it grows with the developing technologies until the beginning of the 21st century. Starting by 1960s, the electric grid has become one of the most vital strength to determine the development level of countries, and grid systems of developed countries have started to be highly interconnected for reliability and economic reasons. The electric grid used to deliver the power to major centres from thousands of centralised power generation eventually evolved for distributing power to small industrial and domestic users in the entire grid system area. Since the usage of electricity rises rapidly, the reliability and efficiency of the traditional power grid have begun to be questioned. The number of interconnections has been increased to achieve the optimum service quality in the grid, and this caused to have a more complex and unstable operational system. Besides, the limitations due to production problems in the case of daily peaks and economic problems both from consumer and producer sides (high cost for the production process caused an increase in consumption tariffs) have signalled that the traditional grid system should be evolved [5].

With advances in communication technologies, limitations on metering have disappeared, and it has led the idea of using smart technologies on the power grid to solve the problems had appeared with the growth of energy demand.

Since in Smart Grid, the usage of renewables matters to production, it also seemed to be the right solution to the growing public concern over environmental damage caused by the energy production in the traditional grid.[6]

2.2. Smart Grid

According to the definition of the European Union Commission Task Force for Smart Grids; Smart Grid is a cost-efficient customer-oriented electricity network that integrates the actions and behaviours of the actors connected to grid system[3]. In a brief explanation, the smart grid is an umbrella technology that contains monitoring, analysis, control and communication capabilities and is applied onto traditional grid systems. This technology gives the following opportunities by applying digital processing and communications onto traditional power grid structure with innovative products and services:

- Efficiency improvements in energy distribution
- Faster restoration in the case of power disturbances
- Low-cost energy consumption tariff with the benefit of cost-efficient production
- Lower electricity rates by reducing peak demand
- High usage of renewable energy systems due to environmental concerns
- Improved security, safety and reliability solutions
- New occupation fields with the usage of smart technologies and innovative products on the grid

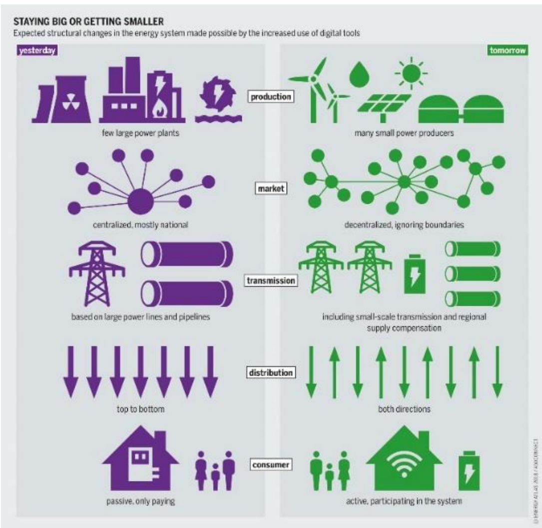

Figure 1: Differences between Traditional and Smart Grids [7]

Since Smart Grid is a new trend in power systems, there is no universal standardisation for its categories of benefits, but they can mainly be divided into five different areas:

Flexibility:
Traditional grid systems were designed by using unidirectional (one-way) energy flows which cause safety and reliability problems in the case of the microgrids to have more production than the consumption [8]. Smart grid gives a more flexible approach by allowing the usage of Photovoltaic (PV) Panels (solar power) on the top of the buildings, wind turbines (wind power), hydroelectric power and distributing the energy from/to electric cars.

Sustainability:
In traditional grid systems, the usage of renewables such as solar panels and wind turbines is a big problem since the infrastructure of the grid does not allow the implementation of distribution (local) level productions (production is more centralised in traditional grid structures). However, in the rare cases of having distributed productions, still, there are some problems with transmission of the produced energy. Since Smart Grid offers a distributed production approach, it allows an efficient implementation on the usage of renewables for energy generation [9].

Reliability:
With the features of fault-detection and self-healing systems, Smart Grid has a great benefit called state estimation. The state estimation gives a more reliable and resilient power distribution system in the condition of natural disasters or malicious attacks [10].

Efficiency:
By reducing the cost of operations and maintenance, the smart grid can minimise the waste and maximise energy production from the usage of renewables [11]. Smart grid coordinates local level production and energy distribution to reduce the congestions and bottlenecks in the grid.

Market-Enabling:
Since Smart Grid is an actor-oriented technology, actors (producers and consumers) have more flexibility about their energy production and consumption strategies. A consumer can follow a strategy for its energy consumption times, levels and periods while a producer can sell its energy by using its strategy for maximising the profit if it has a flexible production enough to follow its plan of action. When talking about Smart Grid, it is also essential to talk about domestic level production since it gives a significant opportunity

to consumers to minimise their cost of energy consumptions by playing an active role in the market with a degree of energy storage.

2.2.1. Smart Metering

Transformation of the traditional grid to Smart Grid infrastructure brought the importance of Information and Communication Technologies (ICT) usage in the field of the electricity network. Implementation of smart grid infrastructures is possible only with the cooperation of ICT components. Smart metering is an essential function enabled by ICT, that is used to measure the bidirectional communication between consumers and producers, and it plays a vital role in the Smart Grid system for energy efficiency.

In other words, a smart meter is an electronic device that is used to record information about the actors in smart grid systems such as voltage levels, power factor and current. The primary purpose of smart meter usage is to give information about consumer behaviours and actions to the consumer to provide energy awareness and to share the consumption information also with producers for monitoring and customer billing. A bidirectional link is used between the central management system and the metering device. Power quality monitoring, ability to record information in real-time or near real-time and regular reports are essential and significant features of smart meters.

It is a common mistake to consider that smart metering and smart grid are the same concepts. Smart Grid may include the usage of smart meters, but the smart meters itself can never create a smart grid since they are the tools for measuring and recording information in the grid and they were installed in the traditional grids before the idea of smart grid concept.

The use of smart meters in grids bring advantages and disadvantages both for consumers and producers [12]:

Advantages of Smart Metering for Consumers:

- It provides a more detailed energy consumption information per consumer.
- It gives some opportunities to follow a different energy consumption strategy for minimising the cost of energy consumption for consumers.
- It reduces the number of system-wide electricity failures and blackouts.

Advantages of Smart Metering for Producers:

- It provides a real-time monitoring system in the grid for producers.
- It ensures a more efficient use of electricity resources.

- It activates dynamic pricing and eliminates periodical manual meter readings.
- It allows optimising the profit by using stored (existing/available) energy.

Disadvantages of Smart Metering for Consumers:

- The installation of a new meter brings the additional cost for the consumer.
- The data representing behaviours and actions of the consumer can violate privacy and security rights.

Disadvantages of Smart Metering for Producers:

- It requires an additional cost for data storage, employee training and development of adequate equipment.
- It is challenging to ensure the security and privacy of metering consumer information
- It is necessary to have a long-term financial commitment for the new software and hardware used in smart metering system.

Smart metering has its infrastructure in grids. Advanced Metering Infrastructure (AMI) is a centralised metering system that allows to measure, collect and analyse the energy usage of consumers and it can also communicate with metering devices by following a schedule or on request. AMI is a combination of hardware, software, consumer energy monitoring technologies and controllers, meter data management software, and producer business systems.

2.2.2. Smart Micro-Grids

When talking about micro-grids, it can be seen that there are some conceptional misunderstandings and confusing descriptions about the grid systems. Micro-grid is a structural deployment concept that is implemented at plant-level on the national grid. In general, the micro-grid concept is a subjective concept that is deployed inside of a plant belonging to a single customer such as campus facilities of hospitals, universities or military bases. However, there are also various examples that it is also implemented by covering more than one plants.

A micro-grid works as one single entity inside of the grid structure while it has its energy production resources, distribution system, consumptions, energy storage and demand management system inside of its boundaries. In some cases caused status changes such as loss of power or electricity supply cost by the national grid, all entities inside of a micro-grid are affected directly since the concept works as a single entity [15]. A micro-grid can also be explained as a group of grid actors located in the same geographical area that has its energy production, distribution, consumption and storage functionalities. It can be connected to national grid infrastructure while it is also able to work disconnected and fully independent depending on its implementation purpose and concept. This feature is vital to increase the reliability of the micro-grid system, especially in the case of power outages on the national grid.

Since the world started to change with the idea of smart technologies and their implementations, using a smart structure that mentioned before became very critical in the sense of economic, environmental and energy efficiency awareness. The idea of using micro-grids gives the environmental, economic and energy efficiency benefits to communities. It covers energy production by using renewables (wind turbines, solar panels, etc.), and it also requires energy storage entities to manage the balance between production and consumption. It can also play an active role in the national grid structure as a market actor by making use of the stored energy on its storage entities. The essential benefits of micro-grids that may change the future of national grid systems can be examined under six subtitles:

Higher Reliability:

To improve the reliability of the national grid system, micro-grids offers an opportunity to have backup power for the communities in some cases such as power outages on the national grid. Since micro-grids can work disconnected to the national grid structure, they can use their productions or storage as backup powers. It supports the continuousness of the power distribution service and pays regard the benefits of customers by giving an independency to the local areas. To do this, a detailed reliability plan identified by authorities for micro-grid communities required to standardise the energy management system (in general via smart technologies), storage system, actions of plants and other components.

Income Growth:

The micro-grid concept helps to generate the revenue of businesses and communities by making them active actors on the market of the national grid. Actors of micro-grids can provide energy distribution services to the other entities on the national grid by following Feed-in Tariff that has been declared by many countries.

Economic Growth:
Micro-grids are a growing industry with new job descriptions and opportunities. Especially with the use of smart technologies in energy management and distribution systems, new work descriptions and job opportunities are increasing day by day as more research, project and engineering skills are required to meet innovative requirements.

Robust Systems:
Independency of micro-grid systems provides a more robust energy supply approach to the local communities. Since each micro-grid community has own renewable energy production resources, energy distribution structure, energy management system and storage entities, they are capable of fending on oneself in any case without being sourced from the broader grid or a large centralised grid system. Increasing robustness also has a significant financial effect on the actors since it makes the grid more price-stable.

Environment-Friendly Approach:
The use of renewables, smart energy management systems and storage entities makes the micro-grids environmental friendly. Therefore, micro-grid communities that actively use renewables for energy production are called green communities, and the concept of creating green communities is one of the most critical parts of EU Clean Energy Package legalised by most of the European countries.

Improvements on Local Energy Distribution Systems:
Developing a micro-grid community relies on a well designed initial plan that covers essential objectives about the development and implementation to create a smart micro-grid community in the best way. In general, these plans are designed by the city administrations or academic institutions that can decide the most suitable locations for the actors in the sense of advanced production and financial benefits. More power generation and distribution alternatives can be explored to make the micro-grid system more efficient, and therefore there are always on-going researches and projects supported by the local authorities to improve the micro-grid community.

2.3. Energetic Communities

With innovations in energy generation technologies increasing day by day, energy production by using renewables is becoming more and more popular since it gives the opportunity of low-cost and efficient production. The use of renewables caused a need for a dynamic, innovative concept to manage the production, distribution and consumption of renewable energy: the concept of Energetic Communities.

The Energetic Community Concept was invented with a revolutionary idea on the grid systems: preventing energy wastage and using the surplus energy to play a role in the market with a competitive price. Since the world of traditional energy distribution has changed with the idea of Smart Grid, the concept of energetic communities can easily be implemented by using the features of smart grid structures smart metering system, artificial intelligent energy distribution algorithms and active actor roles in the grid both on energy production and consumption.

There are various terms and definitions about energetic communities in different projects, researches and reports since the concept is new and it has no standardisation yet. However, definitions of energetic communities used in EU legislative documents (document for EU Clean Energy For Package mentioned in section 3.2) provided by European Parliament and Council of The European Union were used in this work to ensure clarity.

In the market, energy communities work together to play a role as non-commercial market actors by combining non-commercial economic purposes considering environmental and social community objectives. Two directives cover two definitions of energetic communities given by the European Council in EU Clean Energy For Package [13]:

Renewable Energy Communities (REC):

- It has set by The Revised Renewable Energy Directive (EU) 2018/2001.
- They are based on open and voluntary participation. Participation of renewable energy communities must be open for all potential actors without any discrimination criteria.
- The system is effectively controlled by members or shareholders that are located in the same renewable energy community.
- The members or shareholders can be individuals (natural persons), small-medium enterprises (SMEs) or local governing authorities.
- The aim of renewable energy communities is providing environmental and economic benefits by considering the welfare of social community which includes shareholders, members and local actors rather than commercial purposes.

- They have the concept of production-consumption, energy storage and sales by following renewable purchase agreements to distribute the energy within the energetic community and to play a role in the market.

Citizen Energy Communities (CEC):

- It has set by The Revised Internal Electricity Market Directive (EU) 2019/944.
- It is based on open and voluntary participation. The participation of citizen energy communities must be open for all entities, including household actors, without any discrimination criteria.
- The control system in citizen energy communities follows the same structure in renewable energy communities by excluding medium and large size enterprises. It also includes municipalities for the control part.
- Same as the aim of renewable energy communities, citizen energy communities also aim non-financial profits with environmental and economic benefits by considering the welfare of social community which includes shareholders, members and local actors.

Both Renewable Energy Communities and citizen energy communities are obligated to operate on energy production, distribution, aggregation, supply, consumption, energy storage and energy provisioning services, although they have significant conceptual differences in [14]:

Activities:

Activities of renewable energy communities cover all types of renewable energy production for heating and electricity sectors while the activities of citizen energy communities cover both renewable and fossil-fuel production in the electricity sector.

Actors:

All potential actors, including natural persons, micro, small, medium and large enterprises and local authorities can participate in a citizen energy community. Participation in renewable energy communities follows more restrictive rules and participants are allowed only if their actions fit with the economic objectives of the renewable energy community.

Autonomy:

A renewable energy community must be able to be autonomous and be distinctive from individual actors and other members that play a role in the traditional market. On the other hand, there is no autonomy rule for citizen energy communities, but decision-making authority must be limited for the members in the community since they are not engaged in large-scale commercial activities.

Geographical Area:

According to revised Renewable Energy Directive for renewable energy communities, the local community must be located close to renewable energy projects and resources that are owned by the corresponding community. The citizen energy communities do not have any restricted rules to follow for production and consumption related to the geographical area.

Effective Control Systems:

A renewable energy community can be controlled by members (micro, small, medium, large size enterprises) if they follow the restrictions about the geographical area. In contrast, a citizen energy community does not include medium and large size enterprises to play an active role in the control of the energy community.

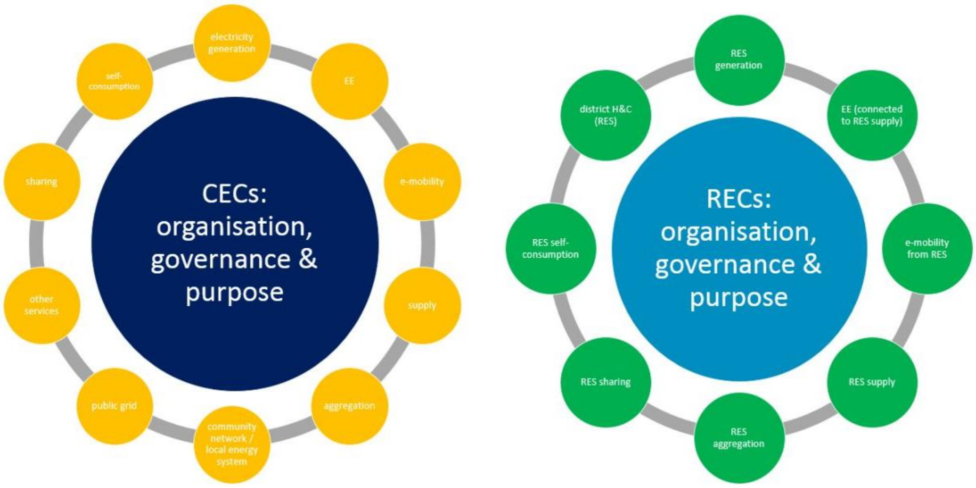

Figure 2: CECs and RECs Activity Comparison[13]

As we can see from the explanations of citizen energy communities and renewable energy communities, the main idea of the concepts is the same. It explains a general solution to actor cooperations by targeting the non-financial profit approach based on ownership and governance to support the energy right of actors in the energy distribution market [14]. Both concepts mainly focus on the benefits of its actors and local areas which they operate on, and they describe a way to improve social communities environmentally and economically.

In general, citizen energy communities and renewable energy communities can face with a conceptional confusion because the descriptions come from different directives announced in different years. Here, the difference between the two energetic communities needs to be addressed in order to make a firm judgment on their explanations. The concept of renewable energy communities is addressed as a type of citizen energy communities where the rules of participation, control system and ownership are slightly different.

2.4. Graph Representation of Energetic Communities

Graphs are sets of applications used to analyse the actors of real-world events such as social, biological, computer or electric power systems and their relationships with each other. In power grids, the structure of the system is represented by using graph theory to measure the performance parameters for characterising and analysing the behaviours of actors and their actions. The information obtained from the results provides a better understanding of the grid system strengths and weaknesses to be ready in the case of system failures that the grid can face and react on real-world. In other words, the use of graph theory to characterise energetic communities allows examining the effects of the changes on the status of the grid system and its entities to measure performance parameters such as reliability and robustness [16].

2.4.1. Graph Theory Implementation

Graph theory provides an abstract representation of a real-world network by using two main components; vertices and edges. Vertices and edges can represent different entities or concepts depending on the type of network that is desired to represent by a graph. In social networks, vertices represent individuals (people), while edges are used to symbolise social relations between individuals. In a computer network structure, vertices can be routers while edges represent links between nodes. On the other hand, in a biological network covers the interactions of proteins between the cells, vertices of the graph represent cells and edges are used to represent chemical reactions between the cells [17]. Similar to all these examples, when the graph theory is used to characterise a power grid, actors of the grid are represented by vertices while the edges are used for the links between the actors.

Graph theory contains many different types of graphs such as directed undirected, connected, disconnected, complete, bipartite, weighted and Hamiltonian. Implementation of graph types varies depending on the properties of real-world networks that are desired to be characterised. To work with various graphs, it is necessary to follow a typical pattern (standard metrics) for analysing them together under the same conditions. Degree distribution, clustering coefficient and network diameters are some of the metrics that provide a better understanding of networks and the behaviour of actors.

The degree distribution of nodes in the complex network is used to classify the system, whether it is a scale-free network. In scale-free networks, the degree distribution follows power-law or has an asymptotic power-law behaviour. The formula can explain Power-law:

$$P(k) \sim k^{-\gamma}$$

Eq-1: Power Law Equation

Where γ is an exponent which is mostly in the range of the values two and three, while k is the degree of the node, the power grids of countries are mostly scale-free networks so that they have a high number of nodes with lower degrees connected to some nodes, called "hubs", that have higher degrees [17-18]. Scale-free networks are robust to random system failures, but they are vulnerable to intentional attacks by targeting specific system entities. Since hubs are connected with many nodes in the network, when the attack is directed to one of the network's hubs, the scale-free network can be affected by the attack burdensomely that it can cause long time loss of power and electricity outages. Nevertheless, having hubs in the network provides also some benefits on system management of the network. The network can be easily configured, controlled and monitored by working on hubs and sometimes even only on one single hub of the network [19].

On the other hand, the vulnerability of small-world networks for both random and directed attacks has an equal probability since small-world networks follow an exponential degree distribution. Power grids mostly behave like single-scale networks, but there are some cases that they can follow a power-law.

A Power Grid Graph is an abstract representation of a power grid system by using graph theory, and the representation does not cover the electric power concepts. It allows analysing power grids from the topological point of view by providing an abstract perspective. The features of power grid graphs can be listed as follows [20]:

Components:

A power grid graph *G(V, E)* includes vertices to represent actors on the grid such as consumers, prosumers, producers and storage entities and edges are links between vertices used for the energy distribution.

Order and Size:

When *V* is the set of vertices and *E* is the list of edges, the order of graph is found by calculating the cardinality of its vertices |*V*| and the size of the graph is found with the formula of |*E*|. So by these definitions, it can be said that for grid actors u and v, if u,v ϵ E, then u and v are neighbours in the same local power distribution community. If u and v are not neighbours, then the representation should be u,v ∉ E. The neighbourhood of vertices can be represented as follows:

$$N(v) = \{x \in V \mid vx \in E\}.$$

Eq-2: Neighbourhood of a Vertex

Degree:

Degree of a vertex *d(v)* is the number of neighbours |*N(v)*| that the vertex is directly connected by edges. (*d(v)*=|*N(v)*|).

Node Degree Distribution:

When *k* is the degree of the node, and it is also a random variable, the formula of probability node degree distribution is:

$$N_k = \{v \in G : d(v) = k\}$$

Eq-3: Node Degree Distribution

Node degree distribution N_k is essential since it gives information about the network mentioned above. If N_k follows the power law, so the power grid is a scale-free network, and it has the robustness of random failures like almost all power grids so far.

Paths:

Each path on the graph *G* can be considered as a subgraph *P*, where the list of vertices *V(P)* is a sublist of the main vertex list *V* and list of edges *E(P)* is a sublist of the main edge list *E*:

$$V(P) = \{x_0, x_1, \ldots, x_l\}, \qquad E(P) = \{(x_0, x_1), (x_1, x_2), \ldots, (x_{l-1}, x_l)\}.$$

Eq-4: Vertices and Edges for Subgraphs

From the given information, it is trivial to check whether a power grid graph is connected; the graph is a connected graph if any vertices $v_k, v_j \in V$. If a path exists between v_k and v_j, then the distance between the vertices $d(v_k,v_j)$ has the minimum value length. On the other hand, if the graph is a disconnected graph, it means that there is no path between v_k and v_j. In other words, a finite path does not exist from v_k to v_j, $d(v_k,v_j) = \infty$. In graph G, there can be more than one paths from v_k *to* v_j, $P_{vk,vj} = \{|P_1|, |P_2|, |P_3|,\ldots, |P_k|\}$. The shortest path is a path from v_k to v_j with the shortest length of all paths in the path list of corresponding vertices, $P_{vk,vj}$. In power grid graphs, shortest paths are commonly used to improve energy-efficient power distribution. Other paths on the path list $P_{vk,vj}$ are generally used in the case of failures or overloads on shortest paths as backup paths.

Betweenness Centrality:

In graph theory, there are several centrality approaches used to identify the most critical vertices of the network. Betweenness Centrality is one of the centrality indicators that measure the importance of vertices based on shortest paths. The betweenness of vertex v:

$$b(v) = \sum_{v \neq s,t} \sigma_{st}(v)$$

Eq-5: Betweenness of a Vertex

Where $\sigma_{st}(v)$ is the boolean value can take the value one if the path between the vertices s and t passes through the vertex v. In power grid graphs, in general, the topological node importance is identified by using betweenness centrality, the most critical node means the most central node of the power grid. By also considering electricity concepts and environmental effects, it can be said that the node with the highest centrality does not have to be the most critical node in real-world grid systems since the electricity flows do not always follow the topological shortest paths.

Weight of Edges:

In graph theory, associated an importance or priority rule to edges is commonly used to make the analysis closer to real-world systems and applications. Edges can have various importance levels, called weights, depending on their role and characteristics in the network and the graphical representations that include weights on edges are called "weighted graphs". In weighted graphs $G(V, E)$, V represents the list of vertices in the graph as usual, where E has three variables v_i,vj, and w (weight of the edge), $E_{i,j,w}=(v_i,v_j,w)$, where $v_i,v_j \in V$ and $w \in$ R.

Reliability Check:
In real-world network infrastructures such as power grids, it is essential to perform analysis about the reliability of the network. In complex network applications such as power grid graphs, reliability is commonly evaluated by removing the nodes; therefore, links to simulate the system faults caused by random failures and targetted attacks. To analyse the behaviour of a network under a random system failure, the nodes to be removed are chosen randomly. On the other hands, to simulate and analyse targeted attacks, hubs of networks must be found by using centrality indicators, in general, between centrality in power grid graphs, and then they can be removed to analyse the behaviour of the system when there is an attack targetted to hub nodes.

In this thesis paper, the grid system of the Piemonte Region (Italy) is analysed by creating a power grid graph with the features mentioned above. Detailed information can be found in section 4.3.

3. Literature Review

There are countless projects and studies performed about smart grid applications, the use of energetic communities, improving their performances and achieving the goal of having smart environmental-friendly power grids. However, for the concern of this thesis, we will focus on projects and studies demonstrating the feasibility and implementation of smart, energetic communities to improve the performance of power grids, taking into account the economic, environmental and innovative benefits.

3.1. Renewable Energy Policies of Countries

The idea of transforming fossil fuel-based energy systems into smart and renewable systems involves highly challenging stages and applications, where most countries are currently working to propose the best, effective and optimal solutions. Countries establish new concepts and ideas to discover the most effective approaches that can fit with their energy policies.

As mentioned in the study about Policies and Strategies for Renewable Energy Development in Indonesia [21], the national energy policy identified in 2014 focuses on increase the use of New and Renewable Energies (NRE) for energy production from 9.3% to 31% by 2050. The NRE concept involves nuclear, hydrogen, hydro, geothermal, bioenergy and other various new and renewable energies. Since almost all provinces in Indonesia have various types of characteristics, the concept mentioned in the Indonesian National Energy Policy cannot be applied in the provincial level. Thus, the deployment approaches and strategies stick to local authorities' decisions. To meet with requirements of national energy policy, each local authority, that response from the corresponding province must provide solutions to formulate its action plan and provincial target on renewables. A provincial target should cover the characteristics of the region that the community located, and analysis should be performed by collecting data contains energy generation and demand behaviours of the region. After a case study performed on five different regions in Indonesia, the authors remarked that the national energy policy and national energy target for the use of renewables in Indonesia should involve more details in provincial level to guide the provincial government's action plan and targets for the use of renewable energies in production. The study has also mentioned about the importance of clarifying energy development target, institutional setup and budgeting mechanism of monitoring the energy action plan's implementation.

In the research paper published in 2016 themed on Small Power Plants and Renewable Energy Policy under Fluctuation of Energy Price and Economic Growth in Thailand [22], five long-term clean energy plans offer solutions for energy production by using renewables; Long-term Power Development Plan, Energy Efficiency Development Plan, Natural Gas Plan, Alternative Energy Development Plan and Fuel Management Plan. The national energy policy has adopted especially the solutions offered by the Alternative Energy Development Plan (AEDP) in 2015. AEDP mainly focuses on establishing energetic green communities for energy production in local systems, on improving security solutions in energy systems, to support developments of alternative energy technology fields and to research, implement and high-efficiency clean energy technologies. The primary purpose of the Alternative Energy Development Plan (AEDP) is to be able to supply 30% of the total energy demand in Thailand by renewable-based energy production by 2036.

In India, the role of renewables in production became highly critical after Indian Electricity Act in 2003. according to the research published in 2007 about Renewable Energy Utilization in India-Policies [23], this act provides roles for independent power production actors in the energy market by providing direct access to energy transmission as well as national distribution systems. In 2007, the publication of The National Action Plan on Climate Change (NAPCC) was one of the most significant steps taken by the Indian government to increase the use of renewables in the energy distribution sector. Especially The National Solar Mission is one of the most critical missions in NAPCC, and it focuses on energy production by solar energy by increasing research and developments with a decentralised generation schema. With the announce of National offshore wind energy policy in 2015, the renewable-based energy production market started to focus on offshore wind energy as another production concept besides solar energy. After regulations on wind-based energy production, National Policy on Biofuels brought a new production concept on bio-fuel usage, especially biodiesel, by guiding processing, distribution, marketing and financial phases. After several innovative steps, finally in 2016 National Policy for Renewable Energy based Micro and Mini-Grids has been announced by MNRE which mainly contain some government energy targets of National Energy Policy of India drafted in 2017 [24]. In the draft of National Energy Policy, the importance of renewable energy technologies was mentioned and energy innovation targeted by 2040 on a five-yearly basis. In the draft of the National Energy Policy, the development of renewable energy technologies was defined, and the steps to be taken for the development of a clean energy system used by 2040 were mentioned. Four key objectives were also defined in the draft; affordable prices, improvements on energy distribution security and independence, higher sustainability and economic growth. By considering these four key objectives of Indian National Energy Policy, innovative technologies, developments, implementations and analysis were proposed in the draft to guide customers to meet economic, environmental and beneficial requirements of future energy targets.

According to information in the research about the Policy Trends of Renewable Energy in Korea [25], that presented in 3rd International Conference on Renewable Energy Research and Applications, the government adopted the idea of "Low Carbon, Green Growth" as a national vision, and there is a vast scope of projects, researches and studies to achieve this objective. According to green growth policy, Korea achieved some critical targets in the fields of green technology development and global green energy production such as establishing 5-year plans for green growth and actions on low-carbon strategies (Framework Act on Low-Carbon). The country became a forerunner in the field of green technology development by the support of 2% GDP into the renewable energy sector. At the 2013 World Energy Congress, Korea mentioned about the role of information and communication technologies in the green energy industries on energy storage and management systems. They also emphasised that low-cost energy production is possible with a renewable-based approach and that energetic communities can play an active role in the market by selling their surplus energy. With the 3rd Master Plan for Promotion of New and Renewable Energy (2009), the government aimed to achieve 11% of the total energy production by renewable and new technologies by 2030. In 2013, another energy plan to support national energy policy called Plan for the Promotion of New and Renewable Energy had been realised to guide the production of heat energy in the buildings with the use of renewable heat energy technologies. In 2014, The 2nd Energy Master Plan represented due to the increasing complexity of energy policies. This plan focused on a supplier-oriented approach instead of consumption-oriented. The goal of the plan was reducing the power consumptions by 15% by 2035. To do this, the government increased the energy tax rate and improved the electrical charging system. Also, according to this plan, instead of having one single large-scale fossil fuel-based energy generation system, the government encouraged the use of renewable energy-based distributed energetic communities [25].

In China, four policies that are considered as law and regulations about energy technologies and renewable productions were issued; The Electricity Law of the PRC, The Energy Conservation Law, The Air Pollution Law of the PRC and The Renewable Energy Law. In the National People's Congress in 2016, the presentation about the Renewable Energy Law of China [26] marked the importance of green energy use in the sector. The Renewable Energy Law involves the feasibility and use of green energy technologies to "increase energy supply, improve energy structure, guarantee energy safety, protect the environment and realise the sustainable development of the economy and society" [26]. According to the research about Renewable Energy Policies and Regulations in the People's Republic of China [27], the country follows a three-level energy policy strategy to encourage the use of renewable systems; the Central Government releases first-level policies, and they contain speeches of governors, general explanations about renewable energy systems and guidance. The Central Government also releases Second-level policies, and they have detailed information about green energy purposes, technologies and objectives. Third-level policies are established by the local authorities such as regional and municipal governments, and they focus on more specific cases such as the deployment of energetic communities to the local energy system. The general aim of China's energy policy is to reach 15.4% green energy use by 2020 and to reach 27.5 by 2050 as a long-term target.

By the guidance of the research to mark the renewable energy policy of Ukraine [28], the implementation of green energy systems was defined under two relevant strategic documents; The Energy Strategy of Ukraine by 2035 and the National Renewable Energy Action Plan by 2020. According to the energy policies of Ukraine, it is targeted to reach 11% of total energy from the use of renewable energy systems by 2020 and 25% by 2035 as a long-term energy production aim. The government encourage the use of renewables in household systems by giving system deployment rights to households' owners such as installing small wind and solar power plants for energy generation since 2020 and selling the generated energy with a feed-in tariff. Ukraine is still working on the deployment issues and improving the efficiency of the system.

Canada was one of the countries that signed The Paris Agreement to strengthen global awareness of climate change [29]. After that, the federal, territorial and provincial majority authorities agreed together to follow a Pan-

Canadian Framework on Clean Growth and Climate Change as mentioned in the Generation Energy Council Report to point out the objectives of Canada's energy transition plan [30]. The essential subjects in this plan are; reduction of the use of coal in nationwide and phaseout it by 2030, declaration of the national strategy for electric vehicles by 2018 and improvement of charging system deployment, implementation of the standard for federal clean fuel, reduction of methane emission especially from the use of oil and gas systems by 2025 and encourage the use of energy management systems.

Five federal drivers for green energy were established; Investment Tax Credit (ITC), Production Tax Credit (PTC), Clean Power Plan (CPP), Modified Accelerated Cost Recovery System Depreciation Schedule (MACRS) and DOE Loan Program according to a paper released to mention the renewable energy policy of US [31]. Investment Tax Credit, Production Tax Credit and MACRS mainly focus on financial concerns for tax credits while the focus of Clean Power Plan is to specify a target emission rate for each state and to aim reduction on total power sector emission by 32% by 2030. Also, State-Level strategies were established, Renewable Portfolio Standards (RPS), Renewable Energy Certificates (RECs), Net Metering & Virtual Metering etc., to specify the implementations, deployments, management, charging methods and the use of renewables on state level [31].

3.2. EU Clean Energy Package and Projects

Transformation of energy production from fossil fuels to green energy resources is highly challenging for the countries. Most of the countries started to adjust their energy generation systems, both technologically and financially by establishing energy policies for renewables that mentioned in section 3.1. Green energy production offers new job descriptions and various economic potentialities to increase the life quality of customers, and it follows the rules of the Paris Agreement to fight with the problem of climate change. To meet with the requirements and decisions about fighting with climate change mentioned in the Paris Agreement, EU encourages institutions, companies and actors in the energy sector to research, study and development on the use of green resources. There is a considerable scope of attempts to improve the quality of energy system services by ensuring the use of clean and fair energy distribution at all levels in the sector. The philosophy behind of EU's attempts for the use of renewables is "Clean Energy For All Europeans". By following this idea, the EU aims to improve the actor roles in the market by giving more opportunities with innovations, and it also targets to provide a high-quality energy distribution interconnections between the countries in the European Union. EU Clean Energy For All Europeans Package [32] is in the centre of all measures that guide the authorities to establish a balance between EU, national and local level decisions. Clean Energy Package is the essential set of energy program ever conferred by the European Commission with great support from the European Parliament and Council to provide all customers in EU access to a more secure, competitive, fair and sustainable energy system by creating an EU Energy Union.

The EU had an early move on green energy concept: with setting the targets in energy policies, the EU was the first one in the sector. In 2010, the 20-20-20 green energy technology was adopted by the EU, which aims 20% reduction on greenhouse gas emission, 20% production by the use of renewable energies, and 20% energy efficiency. By 2020, the EU covered a considerable distance to achieve the goals of 20-20-20 targets. The economy was also affected by the benefits 2020 objectives' achievements: the possibility of GDP growth was observed by using green energy resources, and the employments in the energy sector were increased. With the light of studies, projects and various implementations, the renewable energy system in the EU became cheaper. Because of this reason, wind and solar energy became active actors in the energy market. For the next ten years targets, by 2030, the EU established clear directions for the adaptation of renewable energy systems, and it also provided a balanced legal framework to encourage the investments about renewables by various funding projects. To meet with requirements and rules in Paris Agreement, targets specified in the EU energy policies focus on moving further on the renewable production improvements and on achieving at least 40% reduction of greenhouse gas emission by 2030. To do this, a set of new rules and legislative parameters were defined for coming years, and they were combined under a new framework which is called "Clean Energy For All Europeans Package".

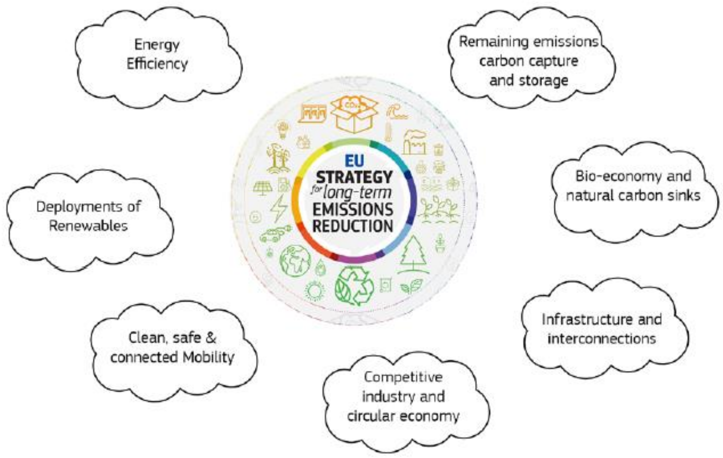

Figure 3: EU Long-Term Strategy [34]

As it can be seen in Figure 3, the clean energy package aids to achieve all EU's long-term renewable targets by defining the directives about energy efficiency, remaining emissions carbon capture and storage, bio-economy and natural carbon sinks, infrastructure and interconnections. Also, it provides guidance on competitive industry and circular economy objectives, clean & safe connected mobility for actors and deployments of renewable resources.

EU Clean Energy For All European Package can basically be combined under five key targets [32]:

Improving the energy efficiency of renewable systems:
As is the aims of all new technology concepts, the primary purpose of transforming the existing energy system to smarter and renewable one is to improve energy efficiency. From the date of the EU energy policy publication to 2020, there is a massive scope of researches, studies and projects to find the best way of renewable systems' deployments for reaching the highest energy efficiency. Therefore, in clean energy package, improving energy efficiency is the most critical target for leading energy systems to the future. The new rules set in the package aims to have almost one third more efficient systems in energy industries which mean at least 32.5% efficiency improvements.

Achieving the global leadership position in renewable energy system deployment:
By encouraging public and private investments in green energy sectors, the EU aims to achieve the global leadership position in the sector with the ambitious target of energy efficiency mentioned above.

Establishing new rules by considering the needs and benefits of actors in the fast-moving renewable industry:
The energy targets highlighted in EU Clean Energy For All Europeans Package are fixed in EU standards, but the new rules can be established for each country to draft National Energy and Climate Plans (NECP) for 2021-2030. The European Commission National Energy and Climate plans will keep track of drafted National Energy and Climate Plans to ensure that they follow the rules and requirements of the Paris Agreement.

Assigning new rights for consumers to make them active actors in the market and ensuring the fairness of the system:
Clean energy package provides high transparency on household billings, and it supports consumer rights to produce their energy by renewable system productions.

Increasing the smartness and security of supply through the use of Information and Communication Technology (ICT):
By using smart technologies that are supported with ICT systems, clean energy package supports improvements of renewable energy systems' security and flexibility.

Besides the environmental benefits, the economic earnings of renewable energy adaptations are highly impressive. To meet with the requirements of the economic sector, it is necessary to modernise the economy concept by considering the effects of renewable systems in the sector. The economic transformation provides new job opportunities and growths in Europe. Clean energy package supports competitive innovations and researches on renewable energy industries. On the other hand, implementing green energy systems derives the quality of services both from the health and life of citizens. It also improves the fairness of customer behaviours in all regions of Europe with the philosophy of "do not leave anyone behind".

EU reserved an impressive budget to support the clean energy transition in Europe by encouraging researches, projects and new technology implementations in between 2014-2020. 20% of EU spendings are currently used to meet climate-related requirements in the Paris Agreement [32]. The European Commission has decided to raise this level to 25% between 2021-2027.

The role of energetic communities during the adaptation period of renewable systems was clearly defined in EU Clean Energy For All Europeans Package. It promotes new rules on self-consumption and local & renewable energy communities to provide a more democratic, fair and flexible energy system for citizens. With these new rules, the citizens can join in energetic communities to make benefits from their energy productions by playing an active role in the energy market. The expectations by 2030 include energetic communities will own 17% of installed wind capacity and 21% of solar. In addition to this, by 2050, 50% of households are expected to play an active role in energy production in the sector [32].

There are countless researches, projects, studies and innovation examples that have been performed in Europe to grasp the objectives of Clean Energy For All Europeans Package such as WiseGrid Project of Spain, HYBRIT Project of Sweden, TILOS Project of Greece and BATCircle Project of Finland.

3.2.1. WiseGrid Project

WiseGrid is a project that involves and validates developed ICT systems for energy grids by following the objectives in Clean Energy Package. The project aims to provide flexibility, security and sustainability to customers in Europe energy grids. It offers smart, stable and secure consumer-oriented solutions by increasing the use of Renewable Energy Sources (RES) and storage technologies.

The demonstrators of WiseGrid Project are located in Italy, Spain, Belgium and Greece (4 large-scale demonstrators) with various social, regional, geographic and technical conditions [33]. All four demonstrators meet under the same strategic goals, which are:

- Creating a demand-response system by using smart technologies such as smart metering and smart home appliances to provide a win-win scheme for both the grid and customers in Europe.
- Developing a smart distribution grid system with the awareness of Virtual Power Plants integration and the use of microgrids.
- Deployment of renewable energy storage systems (batteries, heat accumulators, etc.) to national grid systems' reduce energy losses, improve the balance and management of the network.

- Integrating smart electric mobility services to design a more flexible grid system. Their batteries can be used for storage, and they can play an active role in the grid by supplying energy to the grid actors.

According to the report about the project achievements, published in April 2020 [34], the project proved its quality and efficiency by receiving awards in the field of smart and renewable technologies such as Business Category Award (EUSEW2018), Citizens Category Award (EUSEW2018) and Good Practice of the Year Award. WiseGrid Project was funded from the European Union's Horizon 2020 Research and Innovation Program, which supports innovations, researches and projects in the field of smart and renewable energy systems.

3.2.2. HYBRIT Project

With 7% of $C0_2$ emission, the steel industry is one of the biggest responsible for CO_2 emissions worldwide. Researches proved that the global steel demand would increase rapidly due to the growth of the population by 2050. By this reason, the project HYBRIT [35] was created by the cooperation of three prominent leaders in the industry, LKAB (has the most significant iron ore production in Europe), Vattenfall (has one of the most significant electricity production in Europe) and SSAB (the global leader of high-strength steel industries), to focus on the use of hydrogen for ore-based steel making instead of using coking-coal. This focus makes the project is the world's first fossil-free steel-making project to reduce carbon footprints. The resource of the project done in 2016-2017 shows that fossil-free steel is more expensive than the price of electricity, CO_2 emission and coal. However, by reducing the prices of fossil-free steel and increasing the cost for CO_2 emission, the research shows that, in the future, the fossil-free steel industry will be able to compete with other industries in the market.

In 2018, a pilot study for HYBRIT project started in Lulea, Sweden. This pilot phase is planned to continue until 2024, then the second phase, the demonstration phase, will be performed in 2025-2035 [35].

3.2.3. TILOS Project

This awarded project, the winner of EU Sustainable Energy Award (EUSEW) in energy islands and citizen's award categories, was funded by European Research Project Horizon 2020 and Eunice Energy Group (EEG). It is a private industry member project with the goal of fossil-free based electricity production from renewables by the use of energy islands. Until now, the project has some substantial achievements, development of the optimised energy management system, S4S sustainable storage appliances, implementations of smart grid and security solutions according to the report of the project disposed of by Eunice Energy Group [36].

The project TILOS [37] aims to study on development and implementations of a prototype battery system which also should provide smart grid control systems, microgrid energy management, the use of RESs (Renewable Energy System) and stable grid structure. The pilot implementation phase of TILOS has been completed, and the studies on hybrid power system S4S TILOS is in progress to develop an effective battery-storage system. The idea behind it is to improve the stability of the grid and micro-grid energy management systems. It also provides the rise of renewable energy use.

3.2.4. BATCircle Project

Since the importance of metals has been recognised in the energy storage industries, especially lithium-oil batteries, the battery metal-related industries started to play a very active role in the market to catch the growing trend. Europe specifically encouraged these industries to move forward in the sector because it was known that Asian-based companies dominated the sector and this would make Europe more dependent on the external supply for raw materials and even the end products.

The primary purpose of BATCircle project is to specify approaches of adding value to battery metal-related industries by improving the utilisation of local mineral resources and metal refining systems. The project works with the cooperation of four universities (Aalto, University of Oulu, the University of Eastern Finland and Lappeenranta University of Technology), eight companies, fourteen small and medium enterprises and two research centres (GTK, VTT) [38].

3.2.4. Other Related Projects

Berchidda Energy 4.0" Project:

With a small population (5000 inhabitants) and the economy mainly based on wine production, agriculture and tourism, Berchidda is an old small town in the North East of Sardinia. The necessary transition from traditional grid structure to smart distributed energy systems is highly critical to be an independent energy community, but it is also very challenging for the town because of the economic aspects. By the cooperation between Municipality of Berchidda and Aziende Eettrica Communale (AEC, it is a type of local power company) adaptations of renewable energy production and modifications on existing distribution network are agreed according to EU directives in Clean Energy Package. In the light of the case study in Berchidda [39], it can be said that the first phase of implementations has been completed with the deployment of a new rural energy system to increase the energy production of the area by the use of green resources, photovoltaic panels and wind turbines. The second phase that involves implementing a more modern distribution network structure and energetic community concept in the area will be the next big step to guide the area to the future. This phase will require a strong interaction between public/private stakeholders and citizens since the main aim is increasing the independence of the area from the public grid. To do this, the implementation of energetic communities concept is crucial to create a self-consumption community that consumes the energy produced by itself with the use of renewable energy production technologies. The self-consumption energy efficiency is possible with the proper load shifting, which is highly dependent on smart metering (SM) technologies. Therefore, the authorities attached importance to the implementation of SMs. With the information provided by SMs, the smart energy management software will predict an optimal plan for each consumer based on consumers' behaviours and actions, so it will be able to do load shifting if needed in the grid. This smart technology will provide an energy-efficient distribution system to maximise the performance of the grid. The project also contains a storage support system to store the energy produced by renewable sources, deployment of a new energy carrier to provide the distribution of new energy productions, and a smart grid infrastructure to improve the system efficiency with the use of smart technologies [39].

The COMPILE Project:

To meet with the objectives declared in Clean Energy For All Europeans Package, the project COMPILE was started with considering environmental and socioeconomic benefits in November 2018. The use of energy islands to reduce the carbon emission of production systems is the central concept of the project. The objectives of the project can be listed as follows [40]:

- Supporting the transition from centralised energy system to disıtributed (decentralised) energy systems to have a more flexible infrastructure.

- Encouraging the use of energy communities to give more rights to the citizen for managing their energy consumption and playing an active role in the energy system.
- Optimising the integration and control of energy actors in the grid.
- Storage and electromobility deployments to increase energy efficiency and saving, also to reduce the carbon emission of the local communities.
- Developing smart technological solutions to support the new renewable system and the actors' rights.

The project COMPILE funded by HORIZON2020 program. It contains the studies on five pilot locations with the cooperation of twelve partners and the expected deadline for the project is April 2022 [40].

As a part of COMPILE Project, a case study was published representing the establishment of the first energy community in Slovenia [41]. According to the study, the energy production of the Luce energy community will completely be provided by Renewable Energy Sources (RESs). In the study, the positive effects of energetic communities on the benefits of stakeholders was marked as a conclusion. It was also mentioned that energetic communities have a vital role in the transition from a centralised energy distribution system to a distributed and flexible system [41].

3.3. Complex Networks Theory for Smart Grids

With the need for resources and studies on smart grid technologies to improve the implementation and efficiency of smart technologies on an existing grid system, the use of complex networks analysis became a hot topic. It provides a vast scope of cross-discipline technology such as the implementation of probability and statistics, control theory and graph theory.

According to a survey on complex networks theory for modern smart grid applications published in June 2017 [42], to comprehend the characteristics of the complex networks, various topological metrics are used:

- Degree centrality: to measure the number of connections belong to a node in the graph. It provides information about the connectivity between the nodes.
- Path Length: it refers to the average shortest path length between any two nodes in the graph.
- Clustering Coefficient: it works with the idea of "my friend's friend is also my friend" in social networks. In other words, it is the conditional

probability that two interconnected nodes have a common neighbour node.

- Closeness Centrality: it measures the average distance between a node and other nodes in the network.
- Betweenness Centrality: it gives the importance of a node by measuring its number of existence on the shortest path between two random nodes.

According to these metrics, the complex network's characteristics can be analysed as well as topological characteristics, Statistic Characteristics, and Dynamical Characteristics are crucial in the graph theory implementations. By putting all this information together, a complex network can be represented on graphs to make the analysis easier.

Depending on the complexity, complex networks can be represented in different models to study robustness improvements and vulnerability analysis such as topological-based models, component dependent models, power system dynamical models, and Markovian network models. According to the study, the observations from the comparison between models can be listed as follows [42]:

- Both component dependent models and topological-based models give a basic overview of the vulnerability of structure while in topological-based models, more electrical characteristics about the grid are needed to have an accurate result.
- Since a more detailed approach implemented on power system dynamical models, they can quickly provide real-like solutions of the grid systems. Despite the complexity of these models, they can be applied directly to the real grid structures.

3.4. Energy Communities in Piemonte Region (IT)

According to the case study performed to analyse the energy communities in Piemonte Region [43], the objectives the analysis can be examined under four general topics; encouraging to increase the use of all renewable energy resources, reducing the level of energy consumption in the area by monitoring the energy consumption behaviours and actions of all municipalities and companies, supporting the use of energy-efficient technologies in the community according to the results of financial analysis, and providing an energy management system to manage the productions, consumptions and distributions in the energy community. The paper [43] mainly focused on a case study in Pinerolo (Piemonte, Italy) that covers seven municipalities and around 50 companies.

Pinerolo has 47 thousand buildings, of which 91% are residences. ACEA Pinorolese Industriale Srl. is also located in Pinerolo, which has an essential role in the Italian energy market. ACEA provides biogas and energy production by the use of renewables, and in the case study, this company has a crucial role as a coordinator of the energy community. According to results collected from different questionnaires for both companies and municipalities, and the analysis on energy productions/consumptions in the area, the authors mentioned the importance of energy communities to develop a more sustainable, secure, adequate, and fair energy system in order achieve the objectives such as; improving a cost-effective energy distribution system by smart technologies, providing a more efficient energy network by the use of smart and resilient configurations, and realising the objectives of EU Clean Energy Package [43].

4. Scenario & Methodology

This section contains the data set information, characterization of the grid structure to represent the energy system on graphs, the methodology and algorithms that were used to analyse the efficiency of energy distribution and different approaches & strategies used during the analysis.

The analysis was performed on data collected from a real grid system which is located in the Piemonte Region, Italy.

Figure 4: Case Study Locations in Piemonte

4.1. A Brief Description of Analysis Structure

In the analysis part of the thesis work, scenarios aiming to discover a better energy-efficient distribution were implemented under two different approaches, three cases for three days. A detailed diagram of the analysis structure can be found below.

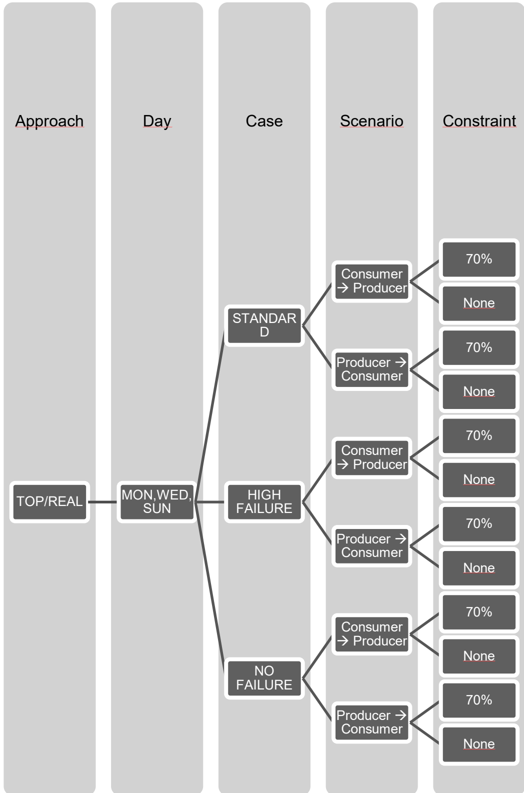

Figure 5: Structure of the Analysis

There are two main approaches implemented for each scenario;

i. The Topological (Abstract) Approach: The idea behind is creating a graph representation of the existing grid by only holding relevant information about nodes and edges except the real distance parameters. So that during the distribution algorithm development, the distances between nodes can be considered as hop counts. This consideration provides an alternative solution to analyse the system independently from its distance constraints.

ii. The Real-Like Approach: With the weighted information of real distances on the edges between source and destination nodes in meters, this approach aims to analyse the energy efficiency of distribution in different scenarios.

To have more reliable results of the actor behaviours, the analysis was performed for Monday, Wednesday and Sunday data given in the primary data set.

For all approaches and days, the energy distribution algorithm was performed under three different cases which are standard distribution case, high path failure case and no (zero) failure case. The purpose of using different cases is to characterize energy distribution patterns under standard distribution, lossy distribution and high-performance distribution conditions to compare the performance parameters. These parameters play a crucial role to analyse the feasibility and implementation standards of energetic communities on the grid systems.

An energetic community mainly consists of three fundamental actions; energy production, distribution and consumption. The efficiency of energy distribution is directly affected by the quality of service standards of the grid. Thus, the goal of green energy use also contains an efficient energy distribution among the actors in the grid. Performing the energy distribution algorithm based on energy demands (consumption trends) and energy production (production availability) provides different perspectives to understand the availability of the existing grid structure for renewable energy production deployments.

In the thesis, mainly, two scenarios were applied to the energy distribution system; the consumption-based distribution scenario and the production-based distribution scenario. Each scenario implementation was analysed by applying direct energy transmission scheme and an energy distribution constraint which allows transmitting 70% of available energy on each producer.

4.1.1. Consumption-Based Energy Distribution Scenario

In this scenario, the distribution algorithm follows a flow pattern from consumer to producers. In other words, the energy distribution is performed according to the consumption needs of actors whose subgroup information is "consumer". In the analysis, the consumer-oriented distribution algorithm was designed by the following steps:

i. Nodes with "consumer" subgroup title are determined in the graph, and they are sorted according to their energy demands (from the highest to lowest demand).
ii. The shortest paths between each consumer and producer are calculated:
    a. In Topological Approach: by using the single-source shortest path algorithm provided by NetworkX library for graph theory implementations on Python.
    b. In Real-Like Approach: by considering real distances in meters provided from linkSet data set.

iii. To measure the path reliabilities, a parameter called "success_binomial" is assigned to each edge to represent the probability of a successful transmission on that link (see in section 4.4).

iv. The consumer node with the highest energy demand is taken from the consumer list that is created after the step i, and it is marked as "current consumer" and all producers in the system are sorted according to:
   a. In Topological Approach: the degree of current consumer node to each producer (from the lowest hop count to the highest one) and success probability of the path between the current consumer and producer nodes (from highest to the lowest one). If degrees of current consumer node is the same for different producers, then the producers are sorted from the one has the highest energy availability to the one has the lowest.
   b. In Real-Like Approach: real distances between current consumer node and each producer node provided from given linkSet data set and success probability of the path between the current consumer to producer nodes (from the highest to the lowest one).

v. The first appropriate producer for the current consumer node is taken from the top of the producer list that is created right after above step depending on the type of approach, and it is marked as "current producer node".

vi. The energy distribution from the current producer to the current consumer nodes is started and if:
   a. The available energy of the current producer node is not enough to satisfy the consumption demand of the current consumer. The current producer's total available energy is set to zero, and the corresponding producer is deleted from the list, and the current consumer's total demand is recalculated again. Then the algorithm goes to step v.
   b. The available energy of the current producer is enough to satisfy the consumption demand of the current consumer, the current consumer's total energy information is set to zero, and the corresponding consumer is deleted from the consumer list. In contrast, the current producer's total available energy is updated. Then the algorithm goes to step iv.

vii. The algorithm is terminated when there is no consumer that needs to satisfy its energy demand in the consumer list, or there is no producer with the available energy to distribute in the producer list.

As can be seen from the steps, the whole energy distribution algorithm was designed as consumer-oriented in this scenario. In traditional grid systems, there is always a massive amount of available energy to satisfy consumer demands. This vast energy availability provides almost a fully continuous service structure while it also requires compelling and costly substance processing methods for energy production. Besides, since the energy production is performed by aiming to be close to the peak level energy consumptions in the area, in the average consumption terms (longer than the peak level consumption terms), consumption energy demands are lower than the productions. It causes a waste of energy & raw material and increases carbon emission. With the use of smart technologies and green renewable productions, the goal is decreasing the carbon emission while also decreasing waste of the energy & raw material by having a balance between consumption and production. To do this, estimations on consumption behaviours are incredibly vital. Thus, the consumption-oriented energy distribution analysis was performed to estimate the residual energy to store for distributing to outer energy communities or for use in the case of power cut in the local community.

4.1.2. Production- Based Energy Distribution Scenario

In this scenario, the distribution algorithm follows a flow pattern from the producer to consumers. In other words, the energy distribution is performed according to the production of actors whose subgroup information is "producer". In the analysis, the production-based (producer-oriented) algorithm was designed by the following steps:

i. Nodes with "producer" subgroup title are determined in the graph, and they are sorted according to their total available energies (from the highest to the lowest one).
ii. The shortest paths between each producer and consumer are calculated:
    a. <u>In Topological Approach:</u> by using single-source shortest path algorithm provided by NetworkX library for graph implementations on Python.
    b. <u>In Real-Like Approach:</u> by considering real distances in meters provided from linkSet data set.

iii. To measure the path reliabilities, a parameter called “success_binomial” is assigned to each edge to represent the probability of a successful transmission on that link (see in section 4.4).

iv. The producer node with the highest total available energy is taken from the producer list that is created after the step i, and it is marked as “current producer node”, and all consumers in the system are sorted according to:

   a. In Topological Approach: the degree of current producer node to each consumer (from the lowest hop count to the highest one) and success probability of the path between the current producer and consumer nodes (from the highest to the lowest). If degrees of current producer node is the same for different consumers, then the consumers are sorted from the one has the highest energy demand to the lowest.

   b. In Real-Like Approach: real distances between the current producer and each consumer node provided from given linkSet data set and success probability of the path between the current producer to consumer nodes (from the highest to the lowest one).

v. The first appropriate consumer for the current producer node is taken from the top of the consumer list that is created right after step iv depending on the type of approach, and it is marked as “current consumer node”.

vi. The energy distribution from the current producer to the current consumer node is started and if:

   a. The available energy of the current producer node is not enough to satisfy the consumption demand of the current consumer. The current producer’s total available energy is set to zero, and the corresponding producer is deleted from the list, and then the current consumer’s total energy is recalculated again. Then the algorithm goes to step iv.

   b. The available energy of the current producer is enough to satisfy the consumption demand of the current consumer, the current consumer’s total energy information is set to zero, and the corresponding consumer is deleted from the consumer list. In contrast, the current producer's total available energy is updated. Then the algorithm goes to step v.

vii. The algorithm is terminated when there is no consumer that needs to satisfy its energy demand in the consumer list, or there is no producer with the available energy to distribute in the producer list.

As it can be seen by the steps, in this scenario, the whole energy distribution concept was designed from a producer-oriented perspective. This perspective follows the same idea used in traditional grid systems which has a centralized distribution system. In the future design of grids, a de-centralized distribution scheme is aimed to deploy. According to deploy this scheme, the energy distribution scenario based on production availabilities is more realistic.

For both energy distribution scenarios based on consumption trends and production availabilities, two different constraints were implemented during the analysis:

- 70% of Available Energy Distribution from Each Producer: The energy distribution scenarios following this constraint aim a more balance energy distribution in the local community since only up to 70% of available energy on a producer node can be distributed to satisfy the consumption demands of other nodes, whereas 30% at least must be saved for the self-saturation process by the producer node itself.
- Energy Distribution with No Constraints (None): The energy distribution scenarios that do not follow any constraint (none) provides a more and quick service solution to distribute the energy among the nodes if the grid network is heterogeneous enough concerning the producer and consumer distributions in the system.

The results collected after the analysis are compared according to their performance metrics in section 5.

4.2. Data Sets

In the analysis, the two data set were used, which are the primary (main) data set and linkSet. Information given in the primary data set was used to characterize the nodes in the graph while linkSet data set that contains connection (link) information was used to describe the edges between the nodes. In thesis analysis, the graph representation of the grid consists of 99 nodes and 118 edges.

The primary data set that was used in the analysis consists of information collected from the grid actors in Piemonte; category, user type, subgroup, renewable source type, location, ID number, hourly energy consumption/production (kWh), total energy consumption/production (kWh).

- Category:

Mainly the actors were categorized under three titles according to their actions in the system; consumers, prosumers and producers.

Consumers:

An actor is called a consumer node if its behaviour in the energy community is based on only energy consumptions. There are three types of consumers appear in the dataset based on their roles in the local community; consumer companies, domestic consumers and consumer municipalities. The consumptions of domestic consumers are out of this thesis's scope since in the analysis the ID numbers are required to keep track information of actors in the grid, and domestic consumers do not have one for now. In future studies, based on the work in this thesis, domestic consumers information can be easily added since the code developed for the analysis was designed to work dynamically based on actor types.

Prosumers:

For an actor to be called a prosumer, it must have an infrastructure to produce energy as well as energy consumption. In the data set, prosumers have both information about their energy consumptions and productions. There are three prosumer types based on their role in the energy community; prosumer municipalities, domestic prosumers and prosumer companies. Domestic prosumers are not included in this thesis work since the required information was not available to perform the analysis. However, the code developed for the analysis is able to work also when the domestic prosumers information is added in data set since it has a dynamic structure based on actor types in the energy community.

Producers:

An actor is titled a producer if the primary purpose of it is to generate energy for the energy community. In the analysis, all producers consist of energy companies with the goal of energy production for the local community.

- User Type:

This section gives information about the actor types in the grid. An actor with type consumer/prosumer/producer can be a company, municipality, or domestic user with respect to its user type title in the data set.

- Subgroup:

The subgroup is a section that provides information about user behaviours. It involves consumer and producer behaviours. For example, if the user is a prosumer, then its subgroup can be either consumer or producer depending on its action at that time. The subgroup of consumers is always “consumer” while it is always “producer” when the actor is a producer in the grid.

- Renewable Source Type:

This type is available for only producers and prosumers with a producer subgroup. It declares the renewable source type used by that actor for energy production. Renewable source type section includes green resources such as biogas, solar PV, biomass, and hydroelectric.

- Location:

This part contains location information of each node in the grid. The case study was performed in the Piemonte Region, Italy (study focuses on a local community located on the south-west side of Torino city).

- ID Number:

Actors in the grid system can be distinguished by unique numbers dedicated to each actor that is called ID numbers. These numbers are fundamentally crucial since the whole analysis ID numbers were used to identify, characterise and analyse the actor behaviours. Besides, in the graph represent the nodes were represented considering their ID numbers.

- Hourly Energy Consumption/Production (kWh):

In the data set, the hourly energy consumption of consumers (or prosumers with consumer subgroup) and generation of producers (or prosumers with producer subgroup) are given in kWh (kilowatt-hour) for each node in the local community on Monday, Wednesday and Sunday.

The actor behaviours were analysed by considering three days of a week in the winter season, Monday, Wednesday and Sunday, to have a more stable point of view about the actions on the grid. In figure 6, it can be seen that the hourly energy consumption of two companies follows different patterns for each day in the analysis.

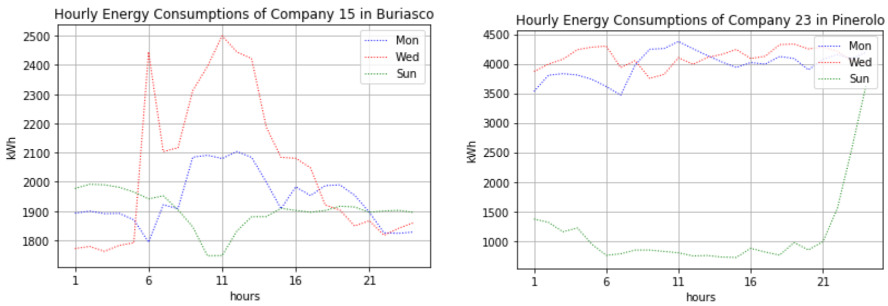

Figure 6: Daily Energy Consumption Comparisons between Company 15 and 23

- <u>Total Energy Consumption/Production (kWh):</u>

In this section of the data set, total Energy consumptions were given in kWh for each node in the local community. During the analysis, the performance of different distribution scenarios was analysed based on daily total energy consumption and production of actors in the system.

Companies with ID numbers 15 and 23 located in Buriasco and Pinerolo have the most active roles for the energy consumptions among the consumer companies. In figure 7, the total energy consumption of companies was shown. Although the total energy consumption can differ for each day, it can be seen that the total energy consumption among companies is dominated by the company 15 and 23 that are located in Buriasco and Pinerolo.

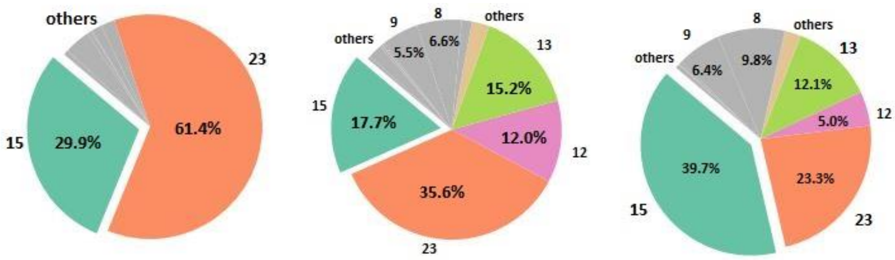

Figure 7: Total Energy Consumption of Companies on Monday, Wednesday and Sunday

Another data set, called linkSet, was used to identify the links between the node actors in the local community. This data set involves four necessary information about the node connections, link ID, source node ID, destination node ID and distance between the source and destination nodes in meters.

4.3. Energy Communities as A Graph

The graph representation of the local community grid was used to characterize the node behaviours and to implement different energy distribution strategies for discovering the best distribution approach in the sense of energy-efficiency. The analysis was performed by using Python programming language and a library that is generally used for graph theory implementations called NetworkX.

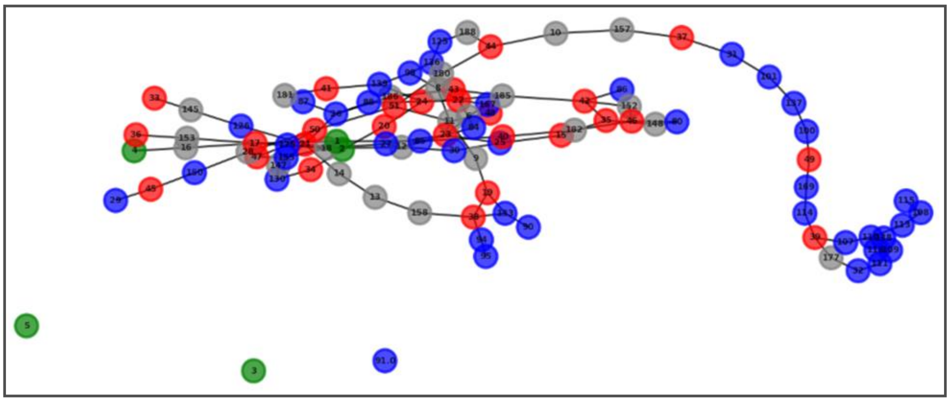

Figure 8: Graph Representation of Grid System in The Analysis

4.3.1. Libraries and Algorithms

A large number of libraries, algorithms and metrics were used in the analysis to obtain, evaluate and visualise the results, however, some of them will be explained under this section since they are common and essential in the field of power grids analysis and complex networks implementations.

Libraries:

- <u>NetworkX:</u>
  NetworkX is a reference library for graph theory analysis that is used explicitly for graph theory implementations on complex networks. It cooperates with Python programming language to create, manipulate, evaluate the various type of structures by covering the features of graph theory mentioned before (in section 2.4.1). It provides flexibility for implementations, rapid development and up-to-date online documentation. The library is an opensource library with a BSD license. Nodes and edges have no custom, and it means that the nodes can be any hashable type of object while edges are tuples. Besides, it also enables to store data for both vertices and edges. The whole library and its features designed to work based on Python programming language that

makes computational network modelling as the main idea by giving the opportunity of fast algorithm design and modelling. Although NetworkX is a very dynamic library to use on network representations and analysis, it is not suggested to perform analysis for large-scale problems since they require a faster approach.

Algorithms and Metrics:

- <u>Single-Source Shortest Path Length:</u>

  NetworkX library provides an algorithm, single-source shortest path length, to find the shortest paths between a specific vertice and all vertices in the graph representation. To understand better single source shortest path length algorithm, first, the concept of Dijkstra's Algorithm is required to be explained, which is an algorithm used for finding the shortest paths between nodes of a graph. It is trivial to find the paths from a single node to many other nodes. Although the original algorithm was designed to find the shortest path between two nodes (a source and a destination node) [44], today it aids to analysis, developments and implementations by using its various types especially the ones that used to find shortest paths from a single source to the whole graph actors.

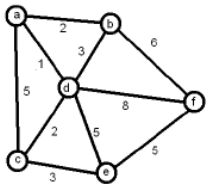

Figure 9: Shortest Path Implementation on the Graph [45]

When we consider the graph in Figure 9, the algorithm follows the steps below:

1. Mark all nodes as *unvisited*, and designate infinite distance to each of them.
2. Mark the first (initial) vertice as the *current* node.
3. Calculate the distance from the current vertice to its all adjacent nodes. If the path from the current node to the adjacent node is shorter than the previous one, then update the value.
4. After all adjacent nodes visited by the current node, mark the current node as *visited.*
5. When all nodes marked as visited, then the algorithm concludes.

In the light of above steps, after running the algorithm on the graph in Figure 3 by considering *node a* as the initial node, the results appear as in the table below:

Node	Distance from "node a"	Path
b	2	a-b
c	3	a-d-c
d	1	a-d
e	6	a-d-e
f	8	a-b-f

Table1: The Result of Shortest Path Algorithm [22]

As it is seen in Table 1, node a is directly connected with node b and d having the distances respectively 2 and 1 while it is not directly connected with nodes c, e and f. Therefore, a shortest path algorithm calculation needed to decide the shortest indirect route between node a and the nodes that they are not directly connected to a.
Single source shortest path algorithm is a variety of Dijkstra's algorithm that was used to find the shortest paths among all actors in the power grid graph. The list of shortest paths was used to simulate energy distribution in the power grid.

- Bernoulli Distribution:
  As a discrete probability distribution of random variables, the Bernoulli distribution takes boolean parameters 0 with probability *(p-1)* and 1 with probability *p*. For any experimental analysis that have two cases, either success or failure, the implementation of Bernoulli distribution can be used for random events. The probability of having k successes out of n independent Bernoulli experiments is called probability mass function of Bernoulli distribution.

$$f(k,n,p) = \Pr(k;n,p) = \Pr(X=k) = \binom{n}{k} p^k (1-p)^{n-k}$$

Eq-6: Probability Mass Function of Bernoulli Distribution

where $k=0,1,2,\ldots,n$. As it can be seen from the formula that, k successful events occur with probability p^k, where the probability of $(n-k)$ failures is $(1-p)^{n-k}$.

Since in power grids failures follow a random pattern, the use of Bernoulli distribution fits with the experiment's needs from the abstract (topological) perspective. In the analysis part of the thesis, Bernoulli distribution was implemented to analyse the reliability of links and the performance of the energy distribution algorithm by considerin different scenarios (mentioned in section 4.1).

4.3.2. Node Characteristics

Additional to node categories from the primary data set, several node types were described to perform the analysis with a more reliable concept. Node types used in the graph representation can be examined under four categories:

- Consumer nodes: A node can be a consumer node if it tends to consume energies generated by producer nodes in the system.
- Producer nodes: A node can be a producer node if it has production systems for energy generation to cover the energy demand of consumers in the grid.
- Transparent nodes: A node can be transparent if it does not have any significant action in the grid to affect the energy distribution. In other words, transparent nodes are the actors that they do not perform any consumption or production action in the grid.
- Cabins: A node is a cabin if it was designed to store residual energy in the system. Cabins can be used to distribute residual energy from an energy community to wider grid or to satisfy the energy demand on the peak times of the local system.

In this thesis work, each node category was represented by using different node colours to distinguish the actors easily; red and blue represents consumers and producers respectively while grey was used for transparent nodes and cabins were represented by green colour.

Graph theory implementation with NetworkX library allows imputing information for each node. In the analysis, all nodes keep four different information; category, subcategory, location and total energy.

4.3.3. Edge Characteristics

The links, called edges, hold specific information to characterize the connection between source and destination nodes according to linkSet data set. Each edge provides data about the source and the destination node, link ID number, the distance between source & destination nodes and the number of pylons on the link. The source and destination nodes are the actors of the grid that are directly connected in the electricity network. The link ID number is a unique number that is used to identify each direct connection between the nodes. A distance metric is a unit of length that describes the distance between the source and destination nodes in meters. The number of pylons on the link is an abstract metric that is used to measure the path reliabilities during the energy distribution (mentioned in section 4.4).

Node and edge characteristics have vital importance for the analysis part of the thesis, especially in the part of energy distribution.

4.4. Calculation of Path Reliabilities

The path reliabilities were calculated to simulate a close experiment to real-life grid systems since in real-life, the path failures caused energy losses can occur. In real grid systems, mostly these path failures happen due to random events on the links that constitute the paths. Therefore, the path failures were calculated by using random events can happen according to probabilities calculated with Bernoulli distribution in the analysis.

In grid energy distribution systems, the generated energy is transferred from one to another via transmission towers until it reaches to the corresponding consumer system. A transmission tower is a tall structure that is used to transfer the high-voltage power along with the long distances. In local energy communities that the distance between the actors is small, utility poles are used to carry the distributed energy to support overhead power lines on sub-transmission and distribution lines. On sub-transmission lines, the higher-voltage energy is carried while the lower-voltage is carried on the distribution line. In the analysis, the failures on the links were calculated by following a similar approach which is by implementing transmission tower-like concept. An interior distribution component called "pylon" was created, and it was assumed that the energy distribution is performed via pylons in the local grid. The distance between each pylon was assigned 365 meters in the case study analysis. It is only an assumption to develop a similar scheme with the real grids since the energy community concept has not been implemented yet; there is no specific information about the real infrastructure. Thus, the path reliability calculations were performed according to this assumption.

In the analysis, it is vital to know the link and the path definitions. According to this thesis work, a link is a connection between the source and the destination node while a path describes a connection structure contains at least one or more links in it. The steps implemented to simulate random path failures in the grid can be explained as follows:

i. According to the case type implemented on the analysis, the source/destination pair are determined by selecting a consumer from the consumer list and a producer from the producer list.
ii. According to the approach followed in the analysis, links between the source and destination nodes are identified to find the shortest path.
iii. The number of pylons, intermediary component, is calculated on each link of the shortest path that gives the fastest connection between source and destination nodes.
iv. The link failure is calculated by considering the failure probabilities between each pylon on the corresponding link.
v. The link is marked as "successful link" if there is no failure occurred between the pylons on the link.
vi. After all links on the path are marked as "successful link", the path between the producer and consumer nodes is marked as "successful path".
    a. If the shortest path between source and destination nodes could not be marked as "successful path" due to the link failures, then it means that the energy distribution cannot be performed successfully and a new path between the nodes is assigned, and the algorithm jumps to step iii.
    b. If the shortest path between source and destination node was marked as "successful path", then it means that the energy distribution is performed successfully.

In the analysis, for standard distribution cases, the failure probability of the connections between pylons was assigned as 0.001 and by following the above algorithm, path reliabilities for each connection were calculated during the energy distribution.

The algorithm to represent failures of real distribution systems provides an abstract view for the analysis. The failures and their probabilities highly depend on the infrastructure and grid behaviours at a different time. Thus, according to deployments and infrastructure of energetic communities, the calculation of path failures can be different from the one that is used in this thesis analysis.

5. Analysis & Results

The analysis was performed by applying two scenarios (based on consumption trends and energy availability) on data collected from the real grid located in Piemonte, Italy on Monday, Wednesday and Saturday in the winter season. For each scenario, the behaviour of the grid as analysed for different cases such as standard distribution, high path failure probability and no path failure probability. Half of the analysis was performed by using a distribution constraint which is transmitting 70% of generated energy on each consumer to satisfy the consumption demands in the local community.

5.1. Self-Saturation Process for Prosumers

Before performing the energy distribution, the actors must be labelled as a consumer or producer. In the primary data set, the actors that have the "prosumer" category can involve both energy consumption and production actions. Thus, before distributing the generated energy, prosumers must satisfy their energy demands by using their own productions. This process is called the self-saturation process. After this process, prosumers that require more energy to satisfy their demands are labelled as "consumers" while prosumers that have more available energy to distribute for satisfying energy demands of other grid actors are labelled as "producers".

As you can see in Appendix A and B, in the graph representation used to characterize the real grid system, the nodes consist of only two types of actors which are consumer and producer and a node can have three types of subcategory such as consumer, prosumer and producer.

NodeID	Category	Sub_Category	Behavior	Saturation Percentage by Itself (%)
45.0	Consumer	Prosumer	Consumer	6.7686
46.0	Consumer	Prosumer	Consumer	0
47.0	Consumer	Prosumer	Consumer	11.5978
48.0	Consumer	Prosumer	Consumer	0.104081
49.0	Consumer	Prosumer	Consumer	11.2759
50.0	Consumer	Prosumer	Consumer	8.93025
51.0	Consumer	Prosumer	Consumer	0

Table 2: Prosumers Labelled as Consumer

NodeID	Category	Sub_Category	Behavior	Saturation Percentage by itself (%)
25.0	Producer	Prosumer	Producer	0
26.0	Producer	Prosumer	Producer	0
27.0	Producer	Prosumer	Producer	0
29.0	Producer	Prosumer	Producer	0

Table 3: Prosumers Labelled as Producer

Table 2 and 3 show the prosumer node information after the self-saturation process. In the graph, prosumers labelled as consumers belong to the consumer category while the producer category contains the prosumers behaves as producers. The last column, called "saturation percentage by itself (%)" shows how much a node satisfied its energy demand by using its own production after the self-saturation process. In the analysis, since the prosumer nodes that are labelled as "producers" have no energy demand, their saturation percentage is zero while some of the prosumers labelled as "consumers" have used their energy production to satisfy their own energy demands.

5.2. Graph and Node Characteristics

This section provides analysis and results that are the same for all approaches and scenarios implemented during the thesis work since the graph representing the power grid has the same structure in all scenarios.

In graph theory implementations of complex networks, the cumulative node degree distribution plays an essential role to classify the represented system as a scale-free or single-scale network [18]. According to degree distribution and cumulative degree distribution of nodes in the analysis (see Figure 10-11), the grid network can be called as a single-scale network since its cumulative degree distribution does not follow a power-law mentioned in section 2.4.1.

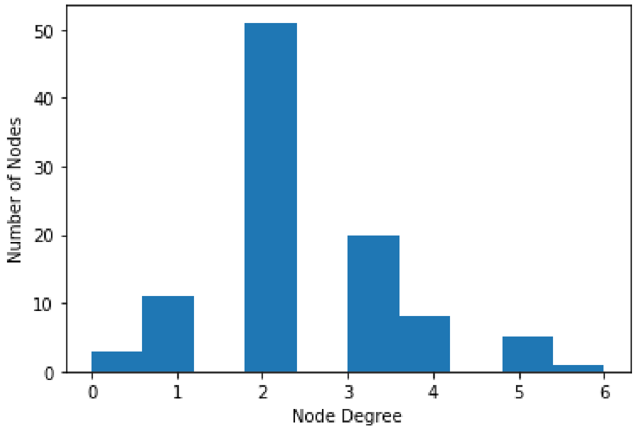

Figure 10: Degree Distribution of The Graph

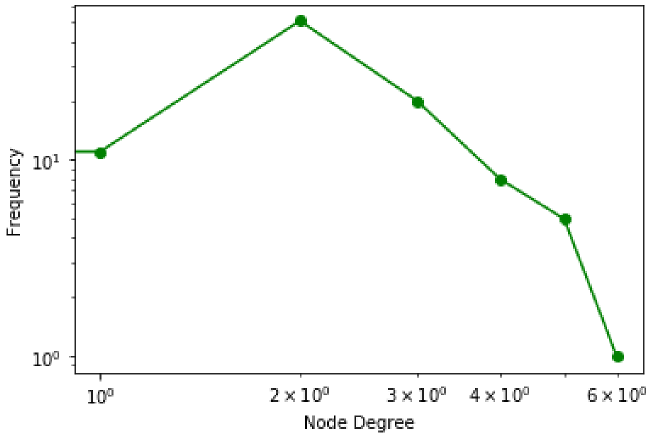

Figure 11: Cumulative Degree Distribution of the Graph

Scale-free networks are more robust in case of cascading failures, and in general, they are vulnerable for targeted attacks. In general, power networks are considered as single-scale networks that they can be affected by the failures easily and the link failures cause the electricity cut-off. Also, a topological analysis of the Italian electric power grid, that was published in 2004 [46] proves that the power grid structure is highly homogeneous by considering the node degree distribution in Italy. Thus, the grid network is called a single-scale network since the cumulative degree distribution of the Italian grid follows an exponential function with the value of 2.5 $e^{-0.55k}$ [46].

Node behaviours are also vital for graph characterization. Therefore, nodes were analysed before starting to energy distribution based on the data collected on different days.

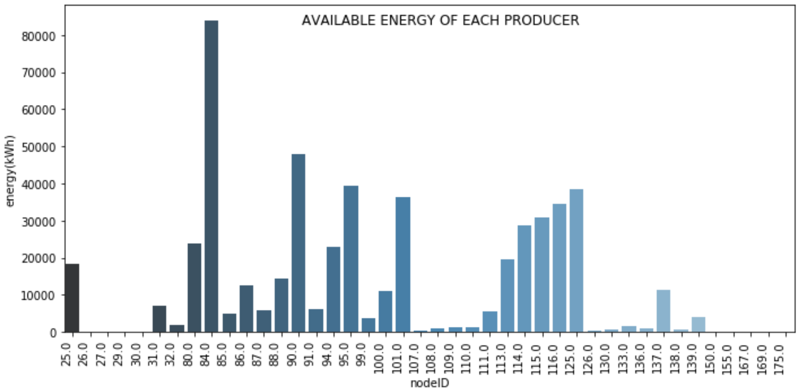

Figure 12: Energy Production per Producers

Figure 12 shows the renewable energy production in the grid network on Monday, Wednesday and Sunday. As can be seen in the figure, the energy production is dominated by the node 84. According to the data set, the 84 is a producer company that generates renewable energy by use of BIOMASS, and it is located in Pinerolo.

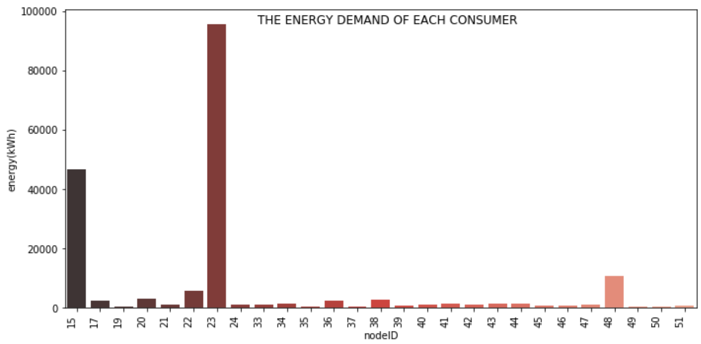

Figure 13: Energy Consumptions per Consumer on Monday

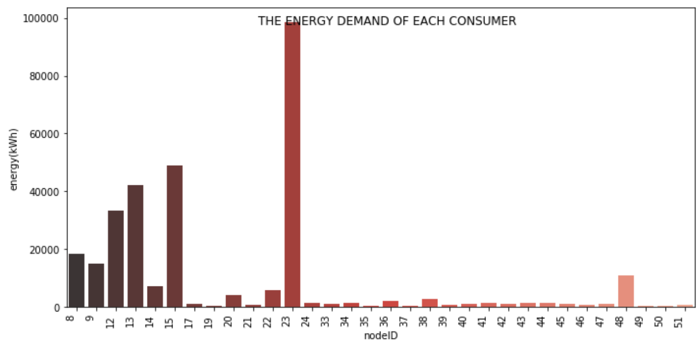

Figure 14: Energy Consumptions per Consumer on Wednesday

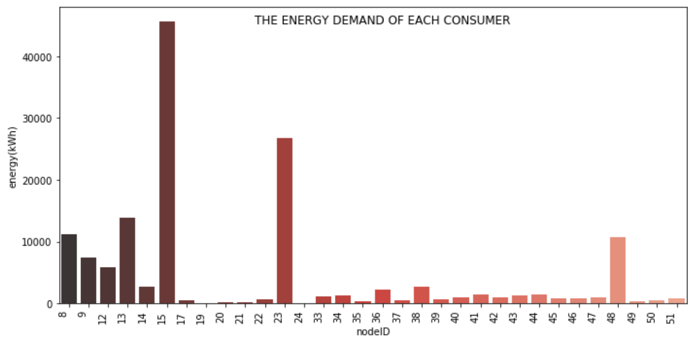

Figure 15: Energy Consumptions per Consumer on Sunday

Figure 13-14-15 show the energy consumption for each consumer node, respectively, on Monday, Wednesday and Sunday. According to the figures above, the consumption is dominated by the node 23 in the system. According to the information given in the main data set, node 23 is a consumer company located in Pinerolo. Considering the location of dominant producer and consumer nodes, the grid system follows a homogeneous behaviour concerning energy generation and consumption actions.

When hourly energy production & consumption of node 23 and 84 are analysed. From the analysis, it can be seen that for node 84 the renewable energy production is constant (see in Figure 16)while the energy consumption of node 23 varies depending on the day (see in Figure 17) since the node is a company and on Sundays, the energy consumption is lower than other days. In the case of low consumer demand, the residual generated energy of the community can be distributed to other communities according to the energetic community description in EU Clean Energy Package.

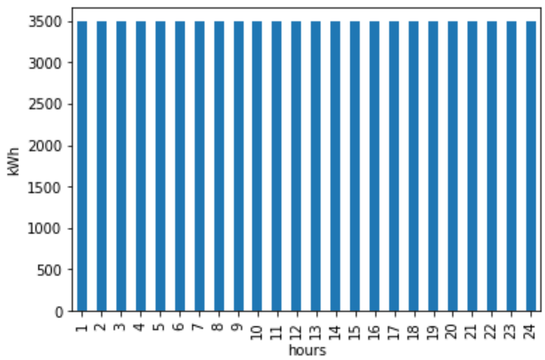

Figure 16: Energy Production of Node 84

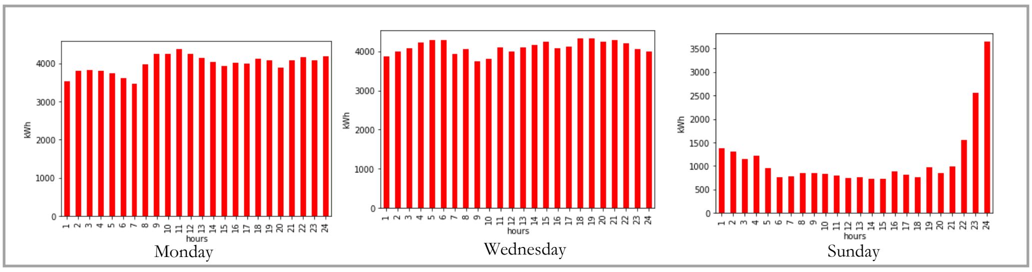

Figure 17: Energy Consumptions of Node 23

5.3. After the Energy Distribution

After the energy distribution in the grid by applying different scenarios and approaches, all energy consumption demands on different days have been satisfied. The consumed and remaining energy fractions after the distribution can be seen in Figure 18. In addition, Table 4 shows the results that were obtained from scenarios and approaches designed to analyse the system on different perspectives.

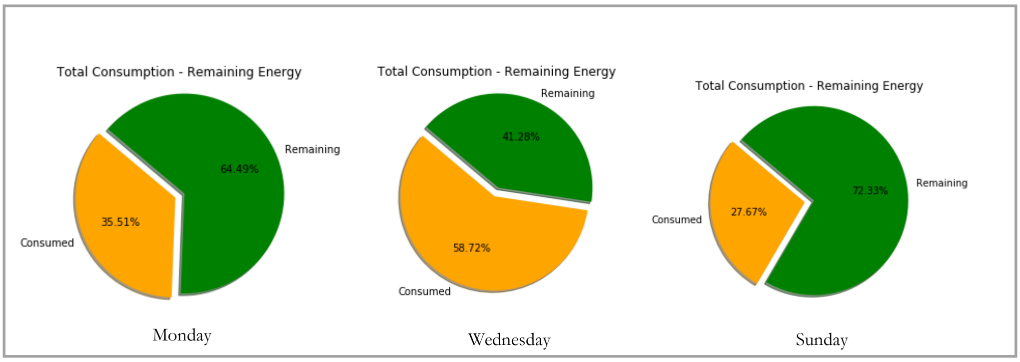

Figure 18: Fraction of Consumed and Remaining Energy After The Distribution

During the energy transmission, a performance parameter called "Product" was defined. The product is a measuring unit that is calculated by multiplying the amount of energy on the link and the distance that the energy crossed by. Therefore, it can be said that the parameter Product provides information about the work of the energy distribution in the system. In the analysis, the product parameter was calculated both for the whole network and each node. The product of the whole network gives the knowledge about the work of the distribution system during the energy transmission while the product per node provides the information about the work of each consumption and production action per node. These measures are essential to analyse the performance of energy distribution scenarios.

- According to product parameter for the whole network (see in Table 4), the total work done by the consumption-based scenarios to distribute the available energy is lower than the work obtained when the production-based scenarios applied. It means that after the implementation of energetic communities using renewable production, the existing grid structure should adopt a consumption-based distribution strategy to provide an efficient distribution.
- The mean of product parameters, that represents the average work to satisfy each consumer node demands (Appendix C and G) or the average work to distribute the generated energy of each producer (Appendix D and H) is higher when the production-based scenarios implemented. Besides, the variance of product parameters for each node has higher values in the production-based implementations. It proves that also for each node, the consumption-based energy distribution provides a better service solution in terms of performance.

The results were analysed according to three distribution cases which are standard distribution, distribution with high path failure probability, and the distribution with no failure. For each case, the performance of the energy distribution system was observed by using the parameter "product" mentioned above. Furthermore, to understand the topological accommodativeness of the grid under different distribution cases in terms of actor locations, a comparison has been made between the approaches of each scenario.

5.3.1. Results After Standard Distribution Case

The results of the analysis performed under the standard energy distribution case can be seen in Table 4. The first three columns of the table contain a description of approaches (topological and real-like) and scenarios (consumption-based and production-based) on different days of the week (Monday, Wednesday and Sunday). The information on the other columns can be explained as follows:

- Available Energy: (Avail. En), this column represents the available energy (total energy production) on the system before the energy distribution.
- Consumer Demands: (Cons. Dem.), this column represents the consumption needs on the system before the energy distribution.

- The Number of Path Failures: (Nº of Fail.) this column shows the number of path failures that occurred during the energy distribution.
- Remaining Energy: (Remain. En), this column contains the amount of energy remained on the system after the energy distribution.
- The Number of Unsatisfied Consumers: (Nº of Un. Sat. Cons.), this column provides the information about the number of consumers that their energy demands have not been satisfied during the energy distribution.
- The Number of Used Producers: (Nº of U. Prod.), this column gives the number of producers that were played an active role to satisfy consumer demands during the energy distribution on the grid.
- The Number of Unfinished Producers. (Nº of UnFin. Prod), this column gives the number of producers that they still have energy remained after the distribution.
- Product (energy X distance): this column involves the parameter product's results, that mentioned above, for each distribution scenario by using topological and real-like approached on Monday, Wednesday and Sunday data.

According to the results in Table 4, there is a considerable difference between the results of the scenarios in terms of energy transmission balance. When the production-based energy distribution is applied, the number of producer nodes that are used to satisfy the energy demand of the grid consumers is explicitly lower than the consumption-based energy distribution results. Thus, it can be said that when the renewable energy production system is applied on the existing grid structure, the energy distribution will be dominated by several producers if the grid continues to follow a production-based energy distribution design.

Figure 20 and 21 show the remaining energies of each producer after the production-based, and the consumption-based distribution is implemented on Monday data with 70% distribution constraint. The total amount of remaining energy is the same after both implementations. As it can be seen from the figures since the consumption-based scenario provides energy distribution opportunity for small-scale energy producers such as node 107,133 and 136 and the medium-scale energy producers such as node 25, the energy distribution is freed from being dominated by large-scale producer nodes.

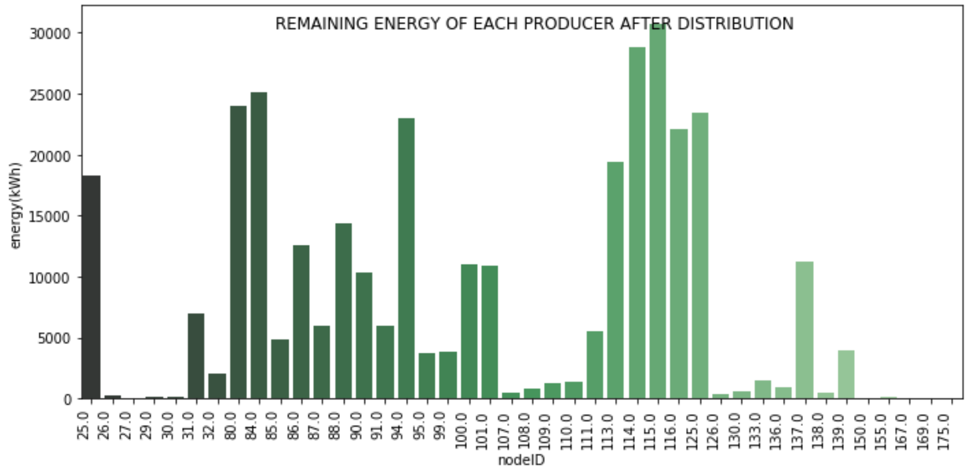

Figure 19: Remaining Energies – Production Based – Standard

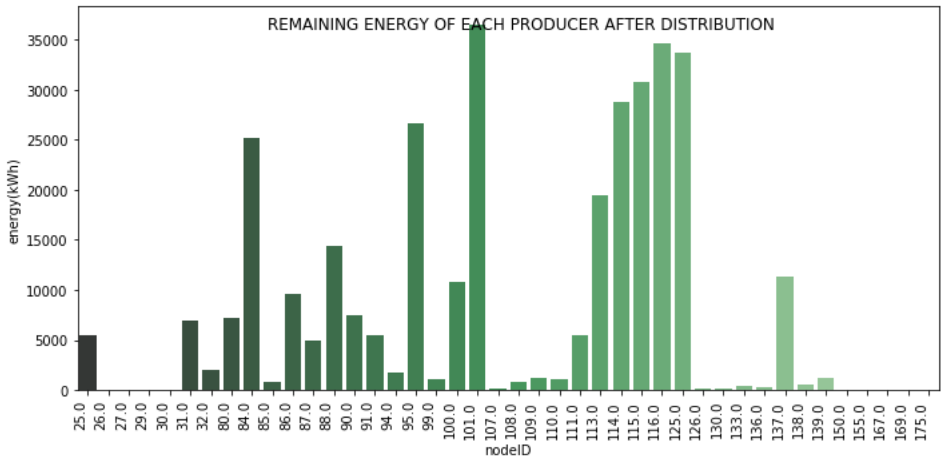

Figure 20: Remaining Energies – Consumption-Based – Standard

When the results are analysed according to implemented approaches, it also gives information about the deployment of energetic communities in the sense of their locations. The use of abstract graph topology neglecting the real distances between the nodes causes a higher entire system work even if the number of path failures is lower than the real-like approach implementation results. According to these results, it can be said that the distance between producers and consumers, the locations of nodes, has a severe impact on the distribution performance. Since the existing grid system was designed to be robust for path failures, even if the number of failures is high, it can still give a better energy distribution service. With the implementation of smart renewable systems, the importance of node distribution in the area will increase since the energy transmission will be transformed from the centralized to a de-centralized distribution system. Thus, as it can also be seen from Table 4, for smart renewable implementations the real-like approach based on distances between the nodes gives a better performance than the topological approach even in case of more path failures.

5.3.2. Results After Distribution with High Path Failure Case

The results of the analysis performed under the energy distribution with a high path failure probability case can be seen in Table 5. The table structure is the same as Table 4 that explained in section 5.3.1.

In the thesis work, the probability of path failures was calculated randomly, as mentioned before. Thus, in the case of energy distribution with high path failure, the number of path failures reaches the lowest value with nine and the highest with seventy-four. After the energy distribution, it can be seen that all consumer demands have been satisfied.

According to the results in Table 5, also in the high path failure probability on the energy distribution system, the number of producers used to satisfy the consumer demands is significantly higher when a consumption-based scenario implemented on the energy transmission system. According to the results in Table 4 and Table 5, even in the high path failure case, the grid system is able to satisfy all consumption needs of consumers. As mentioned before, the grid network is dominated by some specific producers that have large-scale energy production in terms of energy availability. When the results compared between Table 4 and 5, in some cases, it is seen that the work of the distribution system is lower when the high path failure scenario applied. The reason behind is that in the high path failure case if there is a path failure between the dominant producer and consumer, the consumer can be satisfied by small-scale energy producers (small energy communities such as buildings with solar panels, prosumers or producers with less amount of available energy). Since the dominant producers are generally an energy production company, the distance between a dominant producer and a consumer is higher than the producers having a small-scale production. Thus, in some energy distribution cases with high path failure, since the consumer demand has been satisfied by several small-scale producers rather than a single large-scale dominant produce, the work of the system is lower than the standard distribution case. In the analysis, this situation increases the number of producers used during energy distribution.

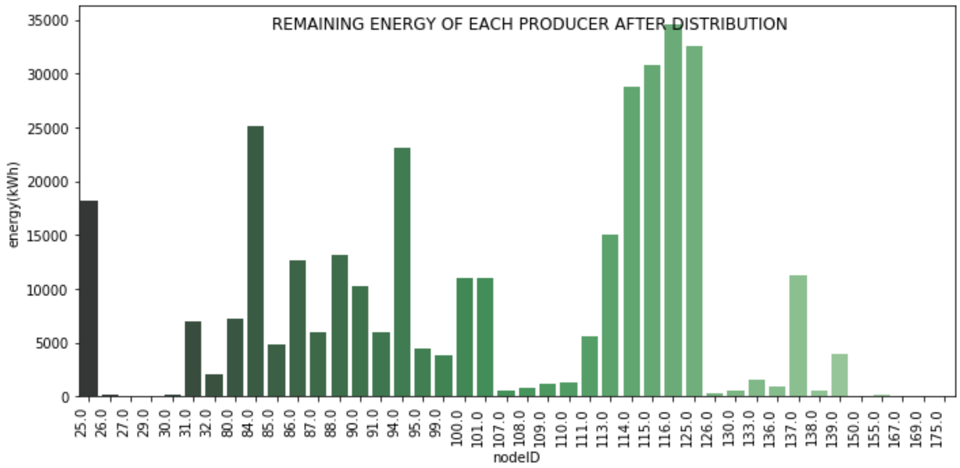

Figure 21: Remaining Energies – Production Based – High Failure

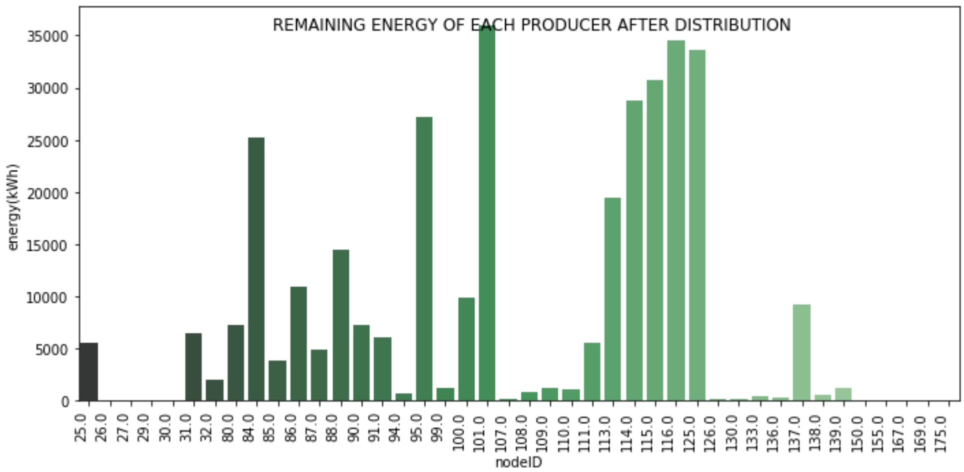

Figure 22: Remaining Energies – Consumption-Based – High Failure

Figure 22 and 23 show the amount of remaining energy per node after the production-based and consumption-based energy distribution with the implementation of 70% distribution constraints on producers under a high path failure case. Even in the high path failure case, the consumption-based proved its balance on the energy distribution system by giving more opportunity to small and medium-scale energy producers such as node 25, 94, 99, and 133.

Besides, the results show that when the production-based energy distribution scenario is followed, in general, the topological approach has a higher performance than the real-like distribution approach. The reason behind is that the real grid system designs do not robust to high path failure cases, and they also follow a production-based distribution scenario. As it can be seen in table 5, when the energy transmission system is designed based on a consumption-based distribution scenario, in general, the real-like approach reaches a higher performance than the topological one. Thus, it can be said that to improve the performance of renewable energy production in energetic communities, adopting a consumption-based distribution scenario for the implementations provides a more robust grid system even under the high path failure situations.

5.3.3. Results After Distribution without Path Failures Case

The results of the analysis performed under the energy distribution without path failures case can be seen in Table 6. The table structure is the same as Table 4 that explained in section 5.3.1.

The results in Table 6 summarises the whole analysis inferences that mentioned in section 5.3.1 and 5.3.2. When a production-based distribution scenario is applied, the system does not have a balance among the producers in terms of available energy distribution. In other words, the energy distribution system is dominated by some specific producers. On the other hand, when a consumption-based distribution is performed, the balance between the producer nodes has a specific effect on the results. Thus, the number of producers used during energy distribution increases significantly.

In order to Figure 24 and 25, when a production-based scenario applied on the distribution system, the small and medium-scale producers are not able to play an active role since the distribution is dominated by some large-scale producers such as node 84. On the other hand, the consumption-based scenario supports a more fair energy distribution idea by providing distribution opportunities for the nodes with a less amount of generated energy such as node 25, 94 and 99.

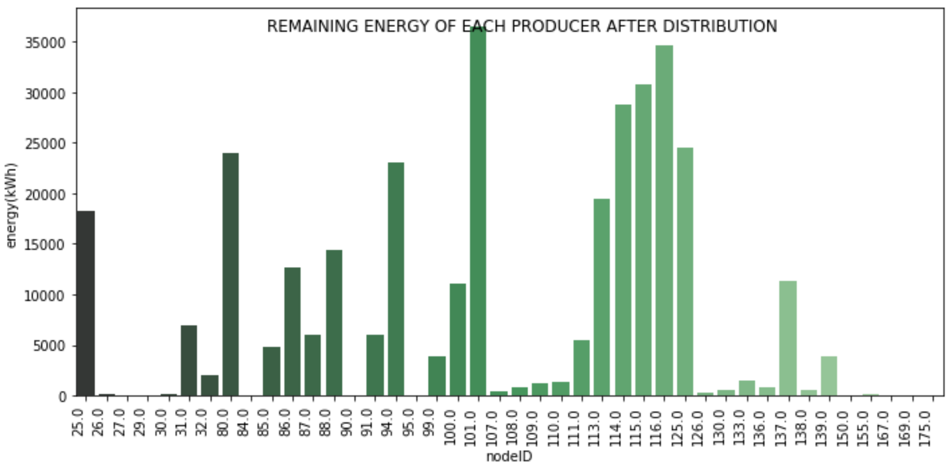

Figure 23: Remaining Energies – Production Based – No Failure

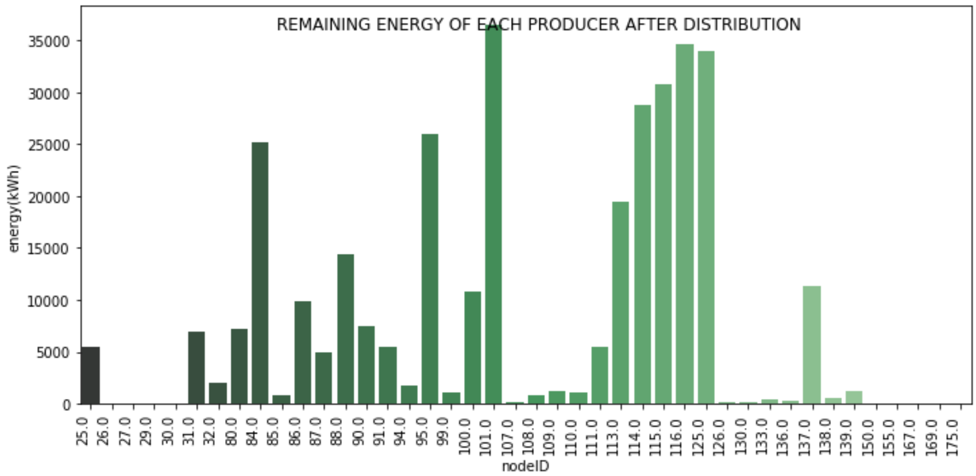

Figure 24: Remaining Energies – Consumption-Based – No Failure

Besides, in terms of performance, there is almost no significant difference between the topological and real-like approach when a production-based energy distribution scenario applied. On the other hand, adopting a consumption-based scenario improves the performance especially considering the implementation of the real-like approach.

The detailed information about the analysis results by considering different energy distribution scenarios can be found in Appendixes. The results collected after a consumption-based scenario implementation (Appendix A to D) shows that the distribution behaviour is more balanced than the one when a production-based energy distribution applied (Appendix E to H).

5.4. The Effect of Implementing Constraints

The idea of energetic communities is based on giving more rights to the actors in the grid for providing the fairness of energy distribution. It means that even the right of actors that have small-scale energy production should be considered to create a self-sustainable energy system and to improve the economy of the local community. Thus, some constraints must be applied to energy distribution for producers.

In this thesis analysis, a distribution constraint, that allows each producer to distribute its 70% of the available energy was implemented. According to the results in the tables above (Table 4, 5 and 6), the number of producer nodes that are used to satisfy the consumption demands in the grid increases by using the 70% distribution constraint since the producer nodes that have small-scale production can find the opportunity to play a role in the energetic communities.

TABLE 4 – RESULTS IN STANDARD DISTRIBUTION CASE

Approach	Day	Scenario & Constraint	Avail. En.	Cons. Dem.	Nº of Fail.	Remain. En.	Nº of Un. Sat. Cons.	Nº of U. Prod.	No UnFin. Prod.	Product (energy X distance)
Top.	**Mon**	**Prod → Cons (70%)**	521625.520	-185233.636	1	336391.884	0	5	38	1750087189.874
Top.	**Wed**	**Prod → Cons (70%)**	521625.520	-306280.749	3	215344.771	0	10	33	4127853312.839
Top.	**Sun**	**Prod → Cons (70%)**	521625.520	-144337.784	1	377287.736	0	4	40	953459480.087
Real-Like	**Mon**	**Prod → Cons (70%)**	521625.520	-185233.636	1	336391.884	0	6	38	1952420600.103
Real-Like	**Wed**	**Prod → Cons (70%)**	521625.520	-306280.749	3	215344.771	0	12	32	4219545578.249
Real-Like	**Sun**	**Prod → Cons (70%)**	521625.520	-144337.784	4	377287.736	0	4	40	975692049.921
Top.	**Mon**	**Prod → Cons (None)**	521625.520	-185233.636	**2**	336391.884	0	5	39	1242189626.182
Top.	**Wed**	**Prod → Cons (None)**	521625.520	-306280.749	2	215344.771	0	8	36	4057479188.242
Top.	**Sun**	**Prod → Cons (None)**	521625.520	-144337.784	0	377287.736	0	3	40	889243515.926

Real-Like	**Mon**	**Prod → Cons (None)**	521625.520	-185233.636	0	336391.884	0	4	39	1183231248.761
Real-Like	**Wed**	**Prod → Cons (None)**	521625.520	-306280.749	3	215344.771	0	19	36	4039315057.144
Real-Like	**Sun**	**Prod → Cons (None)**	521625.520	-144337.784	2	377287.736	0	4	40	923299255.735
Top.	**Mon**	**Cons → Prod (70%)**	521625.520	-185233.636	1	336391.884	0	29	18	1790511822.526
Top.	**Wed**	**Cons → Prod (70%)**	521625.520	-306280.749	2	215344.771	0	33	12	3243631875.209
Top.	**Sun**	**Cons → Prod (70%)**	521625.520	-144337.784	1	377287.736	0	29	22	819238362.208
Real-Like	**Mon**	**Cons → Prod (70%)**	521625.520	-185233.636	2	336391.884	0	29	20	959456301.601
Real-Like	**Wed**	**Cons → Prod (70%)**	521625.520	-306280.749	2	215344.771	0	34	11	3082350898.784
Real-Like	**Sun**	**Cons → Prod (70%)**	521625.520	-144337.784	2	377287.736	0	28	25	574165262.416
Top.	**Mon**	**Cons → Prod (None)**	521625.520	-185233.636	1	336391.884	0	29	21	1199919416.563
Top.	**Wed**	**Cons → Prod (None)**	521625.520	-306280.749	1	215344.771	0	30	16	2218054947.731
Top.	**Sun**	**Cons → Prod (None)**	521625.520	-144337.784	1	377287.736	0	29	23	782015844.042

Real-Like	**Mon**	**Cons → Prod (None)**	521625.520	-185233.636	1	336391.884	0	27	23	724461328.76
Real-Like	**Wed**	**Cons → Prod (None)**	521625.520	-306280.749	2	215344.771	0	31	17	1926362948.517
Real-Like	**Sun**	**Cons → Prod (None)**	521625.520	-144337.784	2	377287.736	0	27	25	521813201.388

Table 4: Analysis of Scenarios Under the Standard Distribution Case

TABLE 5 – RESULTS IN HIGH FAILURE DISTRIBUTION CASE

Approach	Day	Scenario & Constraint	Avail. En.	Cons. Dem.	Nº of Fail.	Remain. En.	Nº of Un. Sat. Cons.	Nº of U. Prod.	No UnFin. Prod.	Product (energy X distance)
Top.	**Mon**	**Prod → Cons (70%)**	521625.520	-185233.636	38	336391.884	0	10	37	1570835706.478
Top.	**Wed**	**Prod → Cons (70%)**	521625.520	-306280.749	28	215344.771	0	13	33	4147139768.778
Top.	**Sun**	**Prod → Cons (70%)**	521625.520	-144337.784	22	377287.736	0	8	40	1005722447.706
Real-Like	**Mon**	**Prod → Cons (70%)**	521625.520	-185233.636	20	336391.884	0	8	38	1619655395.916
Real-Like	**Wed**	**Prod → Cons (70%)**	521625.520	-306280.749	37	215344.771	0	16	31	4662048685.609
Real-Like	**Sun**	**Prod → Cons (70%)**	521625.520	-144337.784	23	377287.736	0	8	40	1019029320.648
Top.	**Mon**	**Prod → Cons (None)**	521625.520	-185233.636	14	336391.884	0	6	39	1174726678.1249168
Top.	**Wed**	**Prod → Cons (None)**	521625.520	-306280.749	38	215344.771	0	13	37	3550691874.550
Top.	**Sun**	**Prod → Cons (None)**	521625.520	-144337.784	20	377287.736	0	7	40	890359666.262

Real-Like	**Mon**	**Prod → Cons (None)**	521625.520	-185233.636	13	336391.884	0	6	39	1370954942.836
Real-Like	**Wed**	**Prod → Cons (None)**	521625.520	-306280.749	32	215344.771	0	13	35	2690171669.444
Real-Like	**Sun**	**Prod → Cons (None)**	521625.520	-144337.784	16	377287.736	0	5	41	970599357.816
Top.	**Mon**	**Cons → Prod (70%)**	521625.520	-185233.636	14	336391.884	0	29	19	1616560025.964
Top.	**Wed**	**Cons → Prod (70%)**	521625.520	-306280.749	74	215344.771	0	40	10	3469074984.479
Top.	**Sun**	**Cons → Prod (70%)**	521625.520	-144337.784	11	377287.736	0	29	23	797936805.442
Real-Like	**Mon**	**Cons → Prod (70%)**	521625.520	-185233.636	26	336391.884	0	31	21	1009440417.067
Real-Like	**Wed**	**Cons → Prod (70%)**	521625.520	-306280.749	63	215344.771	0	38	10	3326772403.442
Real-Like	**Sun**	**Cons → Prod (70%)**	521625.520	-144337.784	11	377287.736	0	28	25	583045689.175
Top.	**Mon**	**Cons → Prod (None)**	521625.520	-185233.636	30	336391.884	0	29	22	1160672354.305
Top.	**Wed**	**Cons → Prod (None)**	521625.520	-306280.749	30	215344.771	0	31	16	2196589013.297
Top.	**Sun**	**Cons → Prod (None)**	521625.520	-144337.784	14	377287.736	0	28	24	858818680.137

Real-Like	**Mon**	**Cons → Prod (None)**	521625.520	-185233.636	9	336391.884	0	27	24	732551040.837
Real-Like	**Wed**	**Cons → Prod (None)**	521625.520	-306280.749	28	215344.771	0	33	17	2088351708.054
Real-Like	**Sun**	**Cons → Prod (None)**	521625.520	-144337.784	10	377287.736	0	29	23	662356277.956

Table 5: Analysis of Scenarios Under the High Failure Distribution Case

TABLE 6 – RESULTS IN NO FAILURE DISTRIBUTION CASE

Approach	Day	Scenario & Constraint	Avail. En.	Cons. Dem.	Nº of Fail.	Remain. En.	Nº of Un. Sat. Cons.	Nº of U. Prod.	No UnFin. Prod.	Product (energy X distance)
Top.	**Mon**	**Prod → Cons (70%)**	521625.520	-185233.636	0	336391.884	0	5	38	1774007465.404
Top.	**Wed**	**Prod → Cons (70%)**	521625.520	-306280.749	0	215344.771	0	10	33	4138867724.754
Top.	**Sun**	**Prod → Cons (70%)**	521625.520	-144337.784	0	377287.736	0	3	40	951533565.200
Real-Like	**Mon**	**Prod → Cons (70%)**	521625.520	-185233.636	0	336391.884	0	5	38	1717413326.681
Real-Like	**Wed**	**Prod → Cons (70%)**	521625.520	-306280.749	0	215344.771	0	11	32	4291284301.981
Real-Like	**Sun**	**Prod → Cons (70%)**	521625.520	-144337.784	0	377287.736	0	3	40	965991171.625
Top.	**Mon**	**Prod → Cons (None)**	521625.520	-185233.636	0	336391.884	0	4	39	1252204740.835
Top.	**Wed**	**Prod → Cons (None)**	521625.520	-306280.749	0	215344.771	0	7	36	4037209170.307
Top.	**Sun**	**Prod → Cons (None)**	521625.520	-144337.784	0	377287.736	0	3	40	892700381.726

Real-Like	**Mon**	**Prod → Cons (None)**	521625.520	-185233.636	0	336391.884	0	4	39	1183231248.761
Real-Like	**Wed**	**Prod → Cons (None)**	521625.520	-306280.749	0	215344.771	0	7	36	4061466846.085
Real-Like	**Sun**	**Prod → Cons (None)**	521625.520	-144337.784	0	377287.736	0	3	40	908979331.495
Top.	**Mon**	**Cons → Prod (70%)**	521625.520	-185233.636	0	336391.884	0	29	17	1676580085.959
Top.	**Wed**	**Cons → Prod (70%)**	521625.520	-306280.749	0	215344.771	0	33	12	3041213556.827
Top.	**Sun**	**Cons → Prod (70%)**	521625.520	-144337.784	0	377287.736	0	30	20	986655104.383
Real-Like	**Mon**	**Cons → Prod (70%)**	521625.520	-185233.636	0	336391.884	0	29	20	957821741.973
Real-Like	**Wed**	**Cons → Prod (70%)**	521625.520	-306280.749	0	215344.771	0	34	12	2966140206.300
Real-Like	**Sun**	**Cons → Prod (70%)**	521625.520	-144337.784	0	377287.736	0	27	25	548388865.734
Top.	**Mon**	**Cons → Prod (None)**	521625.520	-185233.636	0	336391.884	0	28	20	1255927909.419
Top.	**Wed**	**Cons → Prod (None)**	521625.520	-306280.749	0	215344.771	0	30	16	2252339516.805
Top.	**Sun**	**Cons → Prod (None)**	521625.520	-144337.784	0	377287.736	0	28	23	946091665.457

Real-Like	**Mon**	**Cons → Prod (None)**	521625.520	-185233.636	0	336391.884	0	27	22	723657808.564
Real-Like	**Wed**	**Cons → Prod (None)**	521625.520	-306280.749	0	215344.771	0	30	17	1888617396.043
Real-Like	**Sun**	**Cons → Prod (None)**	521625.520	-144337.784	0	377287.736	0	27	25	518383017.975

Table 6: Analysis of Scenarios Under No Failure Distribution Case

6. Conclusion and Future Work

In this research, the main goal was to design and examine different energy distribution scenarios to investigate which are the most suitable to analyse the existing grid system characteristics, trade-off feasibility and benefits obtained by all the involved stakeholders. The results can provide information about the suitability of the future smart renewable production systems by using the energetic communities concept on the existing grid structure. All scenarios and approaches implemented for the analysis were performed according to the power grid network structure, and the graph theory representations were applied to simulate the grid network in Piemonte, Italy. However, it should not be forgotten that the analysis results provide knowledge from the topological point of view by neglecting the electromagnetic process and features of real power grid structures.

Several steps followed to reach the research goal mentioned above. First of all, the actor behaviours were characterized to represent the grid system by using graph theory. A graph simulating the existing power network was created, including all features and characteristics of grid actors.

Different scenarios and approaches were designed to analyse the energy distribution efficiency from various perspectives. The results after the energy distribution of all implemented scenarios were collected to investigate the best distribution idea. The analysis was performed on the results in the light of information obtained on the literature review parts as the final step.

APPROACH	SCENARIO & CONSTRAINT	CASE	Nº OF USED PRODUCERS	Product (kWh*m)
Real-Like	**Prod → Cons (None)**	STANDARD	4	11.83×10^{8}
Real-Like	**Prod → Cons (70%)**	STANDARD	6	19.52×10^{8}
Real-Like	**Cons → Prod (None)**	STANDARD	27	7.24×10^{8}
Real-Like	**Cons → Prod (70%)**	STANDARD	29	9.59×10^{8}
Real-Like	**Prod → Cons (None)**	HIGH FAILURE	6	13.70×10^{8}
Real-Like	**Prod → Cons (70%)**	HIGH FAILURE	8	16.19×10^{8}
Real-Like	**Cons → Prod (None)**	HIGH FAILURE	27	7.32×10^{8}

Real-Like	**Cons → Prod (70%)**	HIGH FAILURE	31	10.09×10^8
Real-Like	**Prod → Cons (None)**	NO FAILURE	4	11.83×10^8
Real-Like	**Prod → Cons (70%)**	NO FAILURE	5	17.17×10^8
Real-Like	**Cons → Prod (None)**	NO FAILURE	27	7.23×10^8
Real-Like	**Cons → Prod (70%)**	NO FAILURE	29	9.57×10^8

Table 7: Comparison of the Scenarios (on Monday-data)

Table 7 shows the comparison between the scenarios in standard, high path failure and no path failure distribution cases when the real-like approach is implemented in the analysis. According to the results, in real-like approach:

- In the Standard Distribution Case: The consumption-based strategy is 38.79% more efficient than the production-based distribution (without constraints). Comparing the strategies allowing the 70% distribution constraint, it can be said that, the production-based strategy 50.87% less efficient than the consumption-based one in terms of the product parameter's values.
- In the Distribution with High Path Failure Case: According to the results of the analysis, the efficiency of the production-based distribution system that worsened up to 16% (if the system does not have any distribution constraint for the producers). The efficiency follows a different behaviour when the production-based strategy is applied with the 70% constraint since the failures between the consumer and large-scale energy producers increases the source fragmentation by allowing small-scale producers to satisfy the consumer demands. On the other hand, although the efficiency of the consumption-based strategies also worsened, it is limited by <7%. Additionally, the consumption-based strategy is 46.56% more efficient than the production-based distribution (without constraints). Comparing the strategies allowing the 70% distribution constraint, it can be said that, the production-based strategy 37.67% less efficient than the consumption-based one in terms of the product parameter's values.
- In the Distribution Without Failures Case: The production-based strategy is 38.88% less efficient than the consumption-based distribution (without constraints). Comparing the strategies allowing the 70% distribution constraint, it can be said that, the consumption-based

strategy 44.26% more efficient than the production-based one in terms of the product parameter's values..

Besides, since the number of producers increases using a consumption-based scheme, the system can be freed from being dominated by the producers having a large-scale energy production with the increase of source fragmentation. Thus, the renewable energetic community implementation can meet with the objectives of EU Clean Energy For All Europeans Package.

Besides, to improve the fairness between the actors of the grid, energy distribution constraints can be assigned for the producers. Although the idea of implementing a distribution constraint on producers affects the distribution system performance negatively, it is still a need in terms of the fairness in the energetic communities. By providing energy distribution opportunities also for the small and medium-scale energy producers, the idea of using constraints improves the fairness among the producers.

In conclusion, the research proved that the existing grid structure is topologically (in terms of node locations) ready for the implementation and deployment of renewable production systems. However, to meet with the requirements of the green self-sustainable community concept, it is still necessary to identify some specifications such as applying a consumption-based energy distribution strategy and assigning production constraints to improve the performance and the fairness of energetic communities. However, since the results are based on the analysis of a limited data set collected from a small local energy community, they may differ depending on the grid systems that the data collected. This research was completed with a hope to open a door for other researches, and hopefully, the large-size green self-sustainable energy communities can be created based on renewable energy production.

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APPENDIX

A.

	NodeID	Category	Sub_Category	Behavior	Saturation Percentage by Itself (%)	Required(-) Energy After Self Feeding*	Producer Nodes used to Saturate This Consumer	Consumer Node Status Info	Saturation Percentage by using Producer Nodes	energyDemand / n of external producer nodes
0	45.0	Consumer	Prosumer	Consumer	6.7686	-807.258949	[125.0]	SATURATED	[93.23139533324066]	807.258949
1	46.0	Consumer	Prosumer	Consumer	0	-815.223292	[86.0]	SATURATED	[100.0]	815.223292
2	47.0	Consumer	Prosumer	Consumer	11.5978	-876.112875	[125.0]	SATURATED	[88.4021540449086]	876.112875
3	48.0	Consumer	Prosumer	Consumer	0.104081	-10734.600610	[139.0, 94.0]	SATURATED	[25.362274036480613, 74.53364473988516]	5367.300305
4	49.0	Consumer	Prosumer	Consumer	11.2759	-306.637530	[169.0, 100.0]	SATURATED	[7.893155872081937, 80.83090716780102]	153.318765
5	50.0	Consumer	Prosumer	Consumer	8.93025	-512.063899	[125.0]	SATURATED	[91.06974827452365]	512.063899
6	51.0	Consumer	Prosumer	Consumer	0	-747.317056	[125.0]	SATURATED	[100.0]	747.317056
7	15.0	Consumer	Consumer	Consumer	NULL	-46659.209000	[80.0, 90.0, 99.0, 136.0, 94.0]	SATURATED	[35.93374246871609, 37.47498824018573, 5.76092...	9331.841800
8	23.0	Consumer	Consumer	Consumer	NULL	-95630.700000	[25.0, 30.0, 27.0, 167.0, 84.0, 133.0, 90.0]	SATURATED	[13.345991193204693, 0.11072109148914455, 0.03...	13661.528571
9	20.0	Consumer	Consumer	Consumer	NULL	-3135.600000	[130.0, 126.0, 95.0]	SATURATED	[12.58011968818526, 6.861883466282876, 80.5579...	1045.200000
10	17.0	Consumer	Consumer	Consumer	NULL	-2244.750000	[155.0, 150.0, 29.0, 175.0, 85.0]	SATURATED	[3.584302138143418, 1.827594712874833 5, 2.4353...	448.950000
11	19.0	Consumer	Consumer	Consumer	NULL	-288.600000	[95.0]	SATURATED	[100]	288.600000
12	21.0	Consumer	Consumer	Consumer	NULL	-984.500000	[95.0]	SATURATED	[100]	984.500000
13	22.0	Consumer	Consumer	Consumer	NULL	-5761.575000	[94.0, 95.0]	SATURATED	[71.93841350217191, 28.06158649782809]	2880.787500
14	24.0	Consumer	Consumer	Consumer	NULL	-1142.300000	[95.0]	SATURATED	[100]	1142.300000
15	33.0	Consumer	Consumer	Consumer	NULL	-1158.866819	[95.0]	SATURATED	[100]	1158.866819
16	34.0	Consumer	Consumer	Consumer	NULL	-1219.428512	[95.0]	SATURATED	[100]	1219.428512
17	35.0	Consumer	Consumer	Consumer	NULL	-351.429644	[86.0]	SATURATED	[100]	351.429644
18	36.0	Consumer	Consumer	Consumer	NULL	-2193.050626	[85.0, 125.0]	SATURATED	[88.30553732508369, 11.694462674916311]	1096.525313
19	37.0	Consumer	Consumer	Consumer	NULL	-458.705036	[91.0]	SATURATED	[100]	458.705036
20	38.0	Consumer	Consumer	Consumer	NULL	-2611.407234	[95.0]	SATURATED	[100]	2611.407234
21	39.0	Consumer	Consumer	Consumer	NULL	-616.773429	[107.0, 110.0]	SATURATED	[54.477055011480346, 45.52294498851965]	308.386714
22	41.0	Consumer	Consumer	Consumer	NULL	-1363.360536	[95.0]	SATURATED	[100]	1363.360536
23	40.0	Consumer	Consumer	Consumer	NULL	-1017.878620	[86.0]	SATURATED	[100]	1017.878620
24	42.0	Consumer	Consumer	Consumer	NULL	-896.307652	[86.0]	SATURATED	[100]	896.307652
25	43.0	Consumer	Consumer	Consumer	NULL	-1224.727397	[26.0, 87.0]	SATURATED	[11.709518194357006, 88.29048180564298]	612.363699
26	44.0	Consumer	Consumer	Consumer	NULL	-1475.252927	[125.0]	SATURATED	[100]	1475.252927

B.

	NodeID	Category	Sub_Category	Behavior	Saturation Percentage by itself (%)	Remaining(+) Energy After Self Feeding*	Consumer Nodes saturated by This Producer	Producer Status Info	Energy Usage Per Consumer(%)
0	25.0	Producer	Prosumer	Producer	0	18232.664000	[23]	FIN	[100.0]
1	26.0	Producer	Prosumer	Producer	0	204.870968	[43]	FIN	[100.0]
2	27.0	Producer	Prosumer	Producer	0	50.842710	[23]	FIN	[100.0]
3	29.0	Producer	Prosumer	Producer	0	78.096774	[17]	FIN	[100.0]
4	80.0	Producer	Producer	Producer	NULL	23952.000000	[15]	FIN	[70.00000000000001]
5	84.0	Producer	Producer	Producer	NULL	83865.600000	[23]	FIN	[70.0]
6	85.0	Producer	Producer	Producer	NULL	4800.000000	[17, 36]	FIN	[51.21994722879413, 48.78005277120587]
7	86.0	Producer	Producer	Producer	NULL	12624.000000	[40, 42, 46, 35]	NOT FIN	[33.0390050038416, 29.092970831074528, 26.4610...
8	87.0	Producer	Producer	Producer	NULL	5976.000000	[43]	NOT FIN	[18.09433935560916]
9	88.0	Producer	Producer	Producer	NULL	14400.000000	[]	NOT FIN	[]
10	90.0	Producer	Producer	Producer	NULL	47952.000000	[23, 15]	FIN	[56.78123831547433, 43.21876168452567]
11	91.0	Producer	Producer	Producer	NULL	6000.000000	[37]	NOT FIN	[7.64508393798662]
12	94.0	Producer	Producer	Producer	NULL	23040.000000	[15, 48, 22]	FIN	[42.84140666401332, 37.66625285606058, 19.4923...
13	95.0	Producer	Producer	Producer	NULL	39528.000000	[22, 20, 38, 41, 34, 33, 24, 21, 19]	NOT FIN	[12.52235052180391, 19.564183616921973, 20.225...
14	99.0	Producer	Producer	Producer	NULL	3840.000000	[15]	FIN	[70.0]
15	100.0	Producer	Producer	Producer	NULL	11040.000000	[49]	NOT FIN	[2.530417987079331]
16	101.0	Producer	Producer	Producer	NULL	36480.000000	[]	NOT FIN	[]
17	107.0	Producer	Producer	Producer	NULL	480.000000	[39]	FIN	[70.0]
18	108.0	Producer	Producer	Producer	NULL	840.000000	[]	NOT FIN	[]
19	109.0	Producer	Producer	Producer	NULL	1200.000000	[]	NOT FIN	[]
20	110.0	Producer	Producer	Producer	NULL	1320.000000	[39]	NOT FIN	[21.27071428862757]
21	111.0	Producer	Producer	Producer	NULL	5520.000000	[]	NOT FIN	[]
22	113.0	Producer	Producer	Producer	NULL	19440.000000	[]	NOT FIN	[]
23	114.0	Producer	Producer	Producer	NULL	28800.000000	[]	NOT FIN	[]
24	115.0	Producer	Producer	Producer	NULL	30720.000000	[]	NOT FIN	[]
25	116.0	Producer	Producer	Producer	NULL	34560.000000	[]	NOT FIN	[]
26	125.0	Producer	Producer	Producer	NULL	38400.000000	[36, 44, 47, 45, 51, 50]	NOT FIN	[5.486513367551453, 31.559782196072376, 18.742...
27	126.0	Producer	Producer	Producer	NULL	307.373169	[20]	FIN	[70.0]
28	130.0	Producer	Producer	Producer	NULL	563.517476	[20]	FIN	[70.0]
29	133.0	Producer	Producer	Producer	NULL	1485.636981	[23]	FIN	[70.0]
30	136.0	Producer	Producer	Producer	NULL	870.890644	[15]	FIN	[70.0]
31	137.0	Producer	Producer	Producer	NULL	11270.349513	[]	NOT FIN	[]
32	138.0	Producer	Producer	Producer	NULL	512.288614	[]	NOT FIN	[]
33	139.0	Producer	Producer	Producer	NULL	3893.393468	[48]	FIN	[70.0]
34	150.0	Producer	Producer	Producer	NULL	58.607046	[17]	FIN	[70.0]
35	155.0	Producer	Producer	Producer	NULL	114.940889	[17]	FIN	[70.0]
36	167.0	Producer	Producer	Producer	NULL	11.184344	[23]	FIN	[70.0]
37	169.0	Producer	Producer	Producer	NULL	38.970549	[49]	FIN	[70.0]
38	175.0	Producer	Producer	Producer	NULL	50.212717	[17]	FIN	[70.00000000000001]
39	30.0	Producer	Producer	Producer	NULL	151.261935	[23]	FIN	[70.0]
40	31.0	Producer	Producer	Producer	NULL	6940.767581	[]	NOT FIN	[]
41	32.0	Producer	Producer	Producer	NULL	2012.051613	[]	NOT FIN	[]

C.

	Consumer	Mean	Variance
0	45.0	1.243450e+07	0.000000e+00
1	46.0	6.562389e+06	0.000000e+00
2	47.0	1.465034e+07	0.000000e+00
3	48.0	2.830617e+07	1.958498e+14
4	49.0	2.231844e+05	4.878265e+10
5	50.0	6.720483e+06	0.000000e+00
6	51.0	6.251726e+06	0.000000e+00
7	15.0	7.319648e+07	2.491360e+15
8	23.0	3.519547e+07	2.788426e+15
9	20.0	9.888263e+06	1.678183e+14
10	17.0	6.044158e+06	1.197702e+14
11	19.0	1.238049e+06	0.000000e+00
12	21.0	7.354225e+06	0.000000e+00
13	22.0	2.126833e+07	8.390321e+13
14	24.0	1.198296e+07	0.000000e+00
15	33.0	9.991535e+06	0.000000e+00
16	34.0	1.409071e+07	0.000000e+00
17	35.0	4.816078e+06	0.000000e+00
18	36.0	2.257982e+07	2.125021e+14
19	37.0	2.905484e+05	0.000000e+00
20	38.0	9.383726e+06	0.000000e+00
21	39.0	1.042818e+05	1.759278e+06
22	41.0	1.443247e+07	0.000000e+00
23	40.0	1.220625e+07	0.000000e+00
24	42.0	4.911466e+06	0.000000e+00
25	43.0	1.928292e+06	3.165997e+12
26	44.0	1.082423e+06	0.000000e+00

D.

	Producer	Mean	Variance
0	25.0	1.23003e+07	0
1	26.0	148967	0
2	27.0	81954.1	0
3	29.0	650239	0
4	80.0	9.24769e+07	0
5	84.0	1.42894e+08	0
6	85.0	3.2544e+07	2.12823e+13
7	86.0	7.12404e+06	9.09162e+12
8	87.0	3.70762e+06	0
9	88.0	NULL	NULL
10	90.0	1.13017e+08	6.65885e+14
11	91.0	290548	0
12	94.0	5.88437e+07	1.03412e+15
13	95.0	1.20877e+07	4.67987e+13
14	99.0	2.46652e+07	0
15	100.0	444052	0
16	101.0	NULL	NULL
17	107.0	105608	0
18	108.0	NULL	NULL
19	109.0	NULL	NULL
20	110.0	102955	0
21	111.0	NULL	NULL
22	113.0	NULL	NULL
23	114.0	NULL	NULL
24	115.0	NULL	NULL

25	116.0	NULL	NULL
26	125.0	8.19031e+06	1.93702e+13
27	126.0	922153	0
28	130.0	535346	0
29	133.0	3.73929e+06	0
30	136.0	6.21616e+06	0
31	137.0	NULL	NULL
32	138.0	NULL	NULL
33	139.0	1.43115e+07	0
34	150.0	458360	0
35	155.0	756035	0
36	167.0	18912.3	0
37	169.0	2316.43	0
38	175.0	425440	0
39	30.0	121259	0
40	31.0	NULL	NULL
41	32.0	NULL	NULL

E.

	NodeID	Category	Sub_Category	Behavior	Saturation Percentage by Itself (%)	Required(-) Energy After Self Feeding*	Producer Nodes used to Saturate This Consumer	Consumer Node Status Info	Saturation Percentage by using Producer Nodes	energyDemand / n of external producer nodes
0	45.0	Consumer	Prosumer	Consumer	6.7686	-807.258949	[125]	SATURATED	[93.23139533324066]	807.258949
1	46.0	Consumer	Prosumer	Consumer	0	-815.223292	[125]	SATURATED	[100.0]	815.223292
2	47.0	Consumer	Prosumer	Consumer	11.5978	-876.112875	[125]	SATURATED	[88.4021540449086]	876.112875
3	48.0	Consumer	Prosumer	Consumer	0.104081	-10734.600610	[90]	SATURATED	[99.89591877636578]	10734.600610
4	49.0	Consumer	Prosumer	Consumer	11.2759	-306.637530	[125]	SATURATED	[88.72406303988295]	306.637530
5	50.0	Consumer	Prosumer	Consumer	8.93025	-512.063899	[125]	SATURATED	[91.06974827452365]	512.063899
6	51.0	Consumer	Prosumer	Consumer	0	-747.317056	[95]	SATURATED	[100.0]	747.317056
7	15.0	Consumer	Consumer	Consumer	NULL	-46659.209000	[95, 101, 116]	SATURATED	[18.500769203629133, 54.72874604453753, 26.770...	15553.069667
8	23.0	Consumer	Consumer	Consumer	NULL	-95630.700000	[84, 90, 95]	SATURATED	[61.38815254933824, 25.119730911819573, 13.492...	31876.900000
9	20.0	Consumer	Consumer	Consumer	NULL	-3135.600000	[95]	SATURATED	[100]	3135.600000
10	17.0	Consumer	Consumer	Consumer	NULL	-2244.750000	[125]	SATURATED	[100]	2244.750000
11	19.0	Consumer	Consumer	Consumer	NULL	-288.600000	[90]	SATURATED	[100]	288.600000
12	21.0	Consumer	Consumer	Consumer	NULL	-984.500000	[95]	SATURATED	[100]	984.500000
13	22.0	Consumer	Consumer	Consumer	NULL	-5761.575000	[95]	SATURATED	[100]	5761.575000
14	24.0	Consumer	Consumer	Consumer	NULL	-1142.300000	[95]	SATURATED	[100]	1142.300000
15	33.0	Consumer	Consumer	Consumer	NULL	-1158.866819	[95]	SATURATED	[100]	1158.866819
16	34.0	Consumer	Consumer	Consumer	NULL	-1219.428512	[125]	SATURATED	[100]	1219.428512
17	35.0	Consumer	Consumer	Consumer	NULL	-351.429644	[125]	SATURATED	[100]	351.429644
18	36.0	Consumer	Consumer	Consumer	NULL	-2193.050626	[125]	SATURATED	[100]	2193.050626
19	37.0	Consumer	Consumer	Consumer	NULL	-458.705036	[125]	SATURATED	[100]	458.705036
20	38.0	Consumer	Consumer	Consumer	NULL	-2611.407234	[90]	SATURATED	[100]	2611.407234
21	39.0	Consumer	Consumer	Consumer	NULL	-616.773429	[125]	SATURATED	[100]	616.773429
22	41.0	Consumer	Consumer	Consumer	NULL	-1363.360536	[95]	SATURATED	[100]	1363.360536
23	40.0	Consumer	Consumer	Consumer	NULL	-1017.878620	[125]	SATURATED	[100]	1017.878620
24	42.0	Consumer	Consumer	Consumer	NULL	-896.307652	[125]	SATURATED	[100]	896.307652
25	43.0	Consumer	Consumer	Consumer	NULL	-1224.727397	[125]	SATURATED	[100]	1224.727397
26	44.0	Consumer	Consumer	Consumer	NULL	-1475.252927	[125]	SATURATED	[100]	1475.252927

F.

	NodeID	Category	Sub_Category	Behavior	Saturation Percentage by itself (%)	Remaining(+) Energy After Self Feeding*	Consumer Nodes saturated by This Producer	Producer Status Info	Energy Usage Per Consumer(%)
0	25.0	Producer	Prosumer	Producer	0	18232.664000	[]	NOT FIN	[]
1	26.0	Producer	Prosumer	Producer	0	204.870968	[]	NOT FIN	[]
2	27.0	Producer	Prosumer	Producer	0	50.842710	[]	NOT FIN	[]
3	29.0	Producer	Prosumer	Producer	0	78.096774	[]	NOT FIN	[]
4	80.0	Producer	Producer	Producer	NULL	23952.000000	[]	NOT FIN	[]
5	84.0	Producer	Producer	Producer	NULL	83865.600000	[23]	FIN	[70.0]
6	85.0	Producer	Producer	Producer	NULL	4800.000000	[]	NOT FIN	[]
7	86.0	Producer	Producer	Producer	NULL	12624.000000	[]	NOT FIN	[]
8	87.0	Producer	Producer	Producer	NULL	5976.000000	[]	NOT FIN	[]
9	88.0	Producer	Producer	Producer	NULL	14400.000000	[]	NOT FIN	[]
10	90.0	Producer	Producer	Producer	NULL	47952.000000	[19, 38, 48, 23]	FIN	[0.76639580432743, 6.934759346517273, 28.50642...
11	91.0	Producer	Producer	Producer	NULL	6000.000000	[]	NOT FIN	[]
12	94.0	Producer	Producer	Producer	NULL	23040.000000	[]	NOT FIN	[]
13	95.0	Producer	Producer	Producer	NULL	39528.000000	[23, 21, 22, 33, 51, 24, 41, 20, 15]	FIN	[36.01219143762729, 2.747817291268215, 16.081...
14	99.0	Producer	Producer	Producer	NULL	3840.000000	[]	NOT FIN	[]
15	100.0	Producer	Producer	Producer	NULL	11040.000000	[]	NOT FIN	[]
16	101.0	Producer	Producer	Producer	NULL	36480.000000	[15]	FIN	[70.0]
17	107.0	Producer	Producer	Producer	NULL	480.000000	[]	NOT FIN	[]
18	108.0	Producer	Producer	Producer	NULL	840.000000	[]	NOT FIN	[]
19	109.0	Producer	Producer	Producer	NULL	1200.000000	[]	NOT FIN	[]
20	110.0	Producer	Producer	Producer	NULL	1320.000000	[]	NOT FIN	[]
21	111.0	Producer	Producer	Producer	NULL	5520.000000	[]	NOT FIN	[]
22	113.0	Producer	Producer	Producer	NULL	19440.000000	[]	NOT FIN	[]
23	114.0	Producer	Producer	Producer	NULL	28800.000000	[]	NOT FIN	[]
24	115.0	Producer	Producer	Producer	NULL	30720.000000	[]	NOT FIN	[]
25	116.0	Producer	Producer	Producer	NULL	34560.000000	[15]	NOT FIN	[36.14264013504354]
26	125.0	Producer	Producer	Producer	NULL	38400.000000	[44, 37, 49, 50, 45, 47, 39, 35, 34, 17, 42, 4...	NOT FIN	[9.824801467420551, 3.0548564451276277, 2.0421...
27	126.0	Producer	Producer	Producer	NULL	307.373169	[]	NOT FIN	[]
28	130.0	Producer	Producer	Producer	NULL	563.517476	[]	NOT FIN	[]
29	133.0	Producer	Producer	Producer	NULL	1485.636981	[]	NOT FIN	[]
30	136.0	Producer	Producer	Producer	NULL	870.890644	[]	NOT FIN	[]
31	137.0	Producer	Producer	Producer	NULL	11270.349513	[]	NOT FIN	[]
32	138.0	Producer	Producer	Producer	NULL	512.288614	[]	NOT FIN	[]
33	139.0	Producer	Producer	Producer	NULL	3893.393468	[]	NOT FIN	[]
34	150.0	Producer	Producer	Producer	NULL	58.607046	[]	NOT FIN	[]
35	155.0	Producer	Producer	Producer	NULL	114.940889	[]	NOT FIN	[]
36	167.0	Producer	Producer	Producer	NULL	11.184344	[]	NOT FIN	[]
37	169.0	Producer	Producer	Producer	NULL	38.970549	[]	NOT FIN	[]
38	175.0	Producer	Producer	Producer	NULL	50.212717	[]	NOT FIN	[]
39	30.0	Producer	Producer	Producer	NULL	151.261935	[]	NOT FIN	[]
40	31.0	Producer	Producer	Producer	NULL	6940.767581	[]	NOT FIN	[]
41	32.0	Producer	Producer	Producer	NULL	2012.051613	[]	NOT FIN	[]

G.

	Consumer	Mean	Variance
0	45.0	1.243450e+07	0.000000e+00
1	46.0	2.571405e+07	0.000000e+00
2	47.0	1.465034e+07	0.000000e+00
3	48.0	1.960160e+07	0.000000e+00
4	49.0	2.830744e+06	0.000000e+00
5	50.0	6.720483e+06	0.000000e+00
6	51.0	6.532982e+06	0.000000e+00
7	15.0	3.799379e+08	4.413578e+16
8	23.0	1.098555e+08	5.488221e+14
9	20.0	3.501488e+07	0.000000e+00
10	17.0	5.780482e+07	0.000000e+00
11	19.0	1.981167e+05	0.000000e+00
12	21.0	7.354225e+06	0.000000e+00
13	22.0	4.314959e+07	0.000000e+00
14	24.0	1.198296e+07	0.000000e+00
15	33.0	9.991535e+06	0.000000e+00
16	34.0	2.279763e+07	0.000000e+00
17	35.0	6.534571e+06	0.000000e+00
18	36.0	6.842864e+07	0.000000e+00
19	37.0	2.340164e+06	0.000000e+00
20	38.0	2.578399e+06	0.000000e+00
21	39.0	1.085662e+07	0.000000e+00
22	41.0	1.443247e+07	0.000000e+00
23	40.0	2.996111e+07	0.000000e+00
24	42.0	2.596800e+07	0.000000e+00
25	43.0	4.407953e+07	0.000000e+00
26	44.0	1.082423e+06	0.000000e+00

H.

	Producer	Mean	Variance
0	25.0	NULL	NULL
1	26.0	NULL	NULL
2	27.0	NULL	NULL
3	29.0	NULL	NULL
4	80.0	NULL	NULL
5	84.0	1.42894e+08	0
6	85.0	NULL	NULL
7	86.0	NULL	NULL
8	87.0	NULL	NULL
9	88.0	NULL	NULL
10	90.0	2.83937e+07	1.37074e+15
11	91.0	NULL	NULL
12	94.0	NULL	NULL
13	95.0	3.59527e+07	1.22741e+15
14	99.0	NULL	NULL
15	100.0	NULL	NULL
16	101.0	6.054e+08	0
17	107.0	NULL	NULL
18	108.0	NULL	NULL
19	109.0	NULL	NULL
20	110.0	NULL	NULL
21	111.0	NULL	NULL
22	113.0	NULL	NULL
23	114.0	NULL	NULL
24	115.0	NULL	NULL
25	116.0	4.34774e+08	0
26	125.0	2.21469e+07	3.96813e+14
27	126.0	NULL	NULL
28	130.0	NULL	NULL
29	133.0	NULL	NULL
30	136.0	NULL	NULL
31	137.0	NULL	NULL
32	138.0	NULL	NULL
33	139.0	NULL	NULL
34	150.0	NULL	NULL
35	155.0	NULL	NULL
36	167.0	NULL	NULL
37	169.0	NULL	NULL
38	175.0	NULL	NULL
39	30.0	NULL	NULL
40	31.0	NULL	NULL
41	32.0	NULL	NULL