*Article*

**Система оценки устойчивости энергетических систем на основе количественных показателей**

**Abstract:**

Пакет "Чистая энергия для всех европейцев" подчеркивает необходимость создания устойчивой критической энергетической инфраструктуры в Европейском союзе. Устойчивость - это новый термин, описывающий способность энергетической системы противостоять потрясениям, вызванным стихийными бедствиями, техническими авариями или преднамеренными угрозами. В данной статье представлена система оценки устойчивости энергетических систем с помощью количественных показателей. Предлагаются две основные группы показателей устойчивости, которые зависят от того, что измеряется в энергетической системе: показатели потенциала (атрибутивные показатели) или показатели эффективности при наличии сбоев (показатели эффективности). Данное исследование сосредоточено на первой фазе устойчивости, когда энергосистема должна поглотить воздействие шока. Подход рассматривает различные сбои (как внутренние, так и внешние) как триггерные события. Особое внимание уделяется будущим потрясениям, влияющим на перспективную энергетическую систему, которая изменится по сравнению с нынешней. Возможности предвидения будущего и потенциал выбранных показателей устойчивости продемонстрированы на примере энергосистемы Литвы. Результаты показали, что наиболее важными факторами, влияющими на устойчивость энергосистемы, являются богатая структура производства электроэнергии и диверсификация как поставок, так и производства в перспективной энергосистеме.

**Keywords:** resilience; quantitative indicators; energy system; energy security; modeling

преднамеренные угрозы (т.е. физические или кибер-атаки). Хотя существует несколько определений устойчивости энергетических систем, нет ни одного, которое было бы согласовано и принято [9,10]. Кроме того, во многих исследованиях понятия энергетической безопасности и энергетической устойчивости переплетаются, и особое внимание уделяется энергетической безопасности, а энергетическая устойчивость анализируется как одно из измерений энергетической безопасности [9,11-15]. В данной работе различия между определениями энергетической безопасности и устойчивости энергетических систем не рассматриваются как критические, и эти два термина используются как взаимозаменяемые.

В литературе, посвященной методам оценки устойчивости энергосистем, в основном рассматриваются два подхода: модельный и индикаторный. Наиболее часто применяемые подходы к моделированию устойчивости энергосистем основаны на стохастических и имитационных моделях [16-20], оптимизационных моделях [21-31] и агент-ориентированных моделях [32-35]. Хотя подходы, основанные на индикаторах, для оценки устойчивости энергосистем все еще ограничены, существует ряд исследований, посвященных индикаторам устойчивости [36-46].

Однако при оценке устойчивости энергосистемы с помощью индикаторов не всегда целесообразно использовать единый или агрегированный показатель устойчивости энергосистемы для измерения ее эффективности. Вместо этого можно использовать систему различных показателей для оценки поведения энергосистемы на разных стадиях устойчивости в условиях сбоев.

Цель данной работы - представить систему показателей для оценки устойчивости энергетических систем с акцентом на их будущие потенциальные ситуации. Использование индикаторов - это метод, который может быть применен для анализа устойчивости в отношении возможностей энергетических систем и их потенциальной деградации и восстановления.

Предложенная система фокусируется на первой фазе устойчивости, когда энергетическая система должна поглотить воздействие шока. Подход рассматривает различные нарушения (как внутренние, так и внешние) в качестве триггерных событий, и особое внимание уделяется будущим потрясениям, влияющим на перспективную энергетическую систему, которая изменится по сравнению с текущей системой. Таким образом, возможности будущего прогнозирования некоторых показателей устойчивости анализируются в данном исследовании путем демонстрационных расчетов. Для этого используется инструмент моделирования энергосистемы для энергетического планирования.

Структура оставшейся части статьи выглядит следующим образом: В разделе 2 представлен предлагаемый методологический подход; в разделе 3 описана модель энергетической системы, основные допущения, данные и сценарии, использованные для демонстрации методологии; результаты моделирования обсуждаются в разделе 4; основные выводы исследования обобщены в заключении, раздел 5.

2. **Показатели устойчивости энергетической системы**

В этом разделе определен набор показателей, которые можно использовать для определения устойчивости энергосистемы. Основное внимание уделяется первой фазе устойчивости, когда показатели оценивают, как энергетическая система поглощает воздействие сбоя.

Предлагаемая система показателей разработана с учетом:

- Экспертное мнение авторов и многолетний академический и практический опыт в энергетическом секторе, включая энергетическую безопасность, критические энергетические инфраструктуры, надежность, анализ рисков и смежные темы. Опыт авторов охватывает как национальный, так и международный уровни.

- Обзор литературы других авторов по устойчивости энергетических систем

Наиболее важной задачей, связанной с устойчивостью энергетических систем, является измерение способности энергетической системы поглощать или ограничивать воздействие сбоев и измерение производительности энергетической системы в условиях сбоев. Такой подход к измерению устойчивости соответствует метрикам устойчивости, предложенным в [41,42].

Показатели устойчивости, которые измеряют способность или потенциал системы к поглощению сбоев, соответствуют метрикам, основанным на атрибутах. Показатели, основанные на атрибутах, обычно демонстрируют характеристики энергетической системы и ее текущую устойчивость по сравнению с другими системами. Эти показатели измеряют, что делает энергетическую систему более или менее устойчивой. Устойчивость измеряется на основе атрибутов энергетической системы или ее компонентов, например, количества генераторов на площадке.

Дополнительные показатели этой группы, которые демонстрируют не физический потенциал системы, а организационные возможности, также могут быть использованы для измерения устойчивости. Как правило, они включают в себя смягчение последствий и управление чрезвычайными ситуациями, планы на случай чрезвычайных ситуаций, стратегии, обучение персонала, знания, организации, людей, обслуживание центров управления и другие ресурсы для выполнения необходимых функций реагирования на чрезвычайные ситуации. Однако эти показатели в основном зависят от конкретного предприятия или страны, основаны на различных требованиях и стандартах и в основном оцениваются с помощью качественного подхода. Поскольку в данном исследовании основное внимание уделяется количественным показателям устойчивости, вышеупомянутые меры выходят за рамки исследования и не рассматриваются в нем более подробно.

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*2.1. Показатели способностей/возможностей*

*I*1. **Количество точек входа**

Этот показатель измеряет общее количество всех точек входа в систему поставок топлива, используемого для производства электроэнергии. Такие виды топлива, как природный газ, нефть и уголь, могут поступать в энергосистему в целом через морские порты, терминалы сжиженного природного газа, трубопроводы и железные дороги. В случае перебоев в каком-либо пункте поставки могут быть увеличены в других, не затронутых. Это позволяет защитить внутренние поставки от перебоев. Чем больше точек входа в энергетическую систему, тем менее она уязвима к перебоям в поставках топлива. Показатель измеряется количеством (N) различных точек входа для различных видов топлива, используемых для производства электроэнергии. Показатель демонстрирует способность энергосистемы переносить перебои в поставках как отечественного, так и импортного топлива.

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*I*1 = *N*/*D*max · *U* (1)

где N - количество точек входа для топлива, используемого для производства электроэнергии, Dmax - максимальный спрос на электроэнергию, а U - выбранная единица максимального спроса на электроэнергию (например, на 1000 МВт).

Например, если в стране А имеется 5 точек входа для всех видов топлива, используемых для производства электроэнергии, а максимальный спрос на электроэнергию составляет 2000 МВт, то показатель будет оцениваться как 2,5 точки входа в среднем на 1000 МВт максимального спроса на электроэнергию. Аналогичным образом, если в стране B имеется 8 точек входа для всех видов топлива, используемых для производства электроэнергии, а максимальный спрос на электроэнергию составляет 4000 МВт, показатель будет оцениваться как 2 точки входа, в среднем на 1000 МВт максимального спроса на электроэнергию. Такие расчеты приведут к снижению устойчивости на 20% в стране B по сравнению со страной A.

Более высокое значение этого показателя свидетельствует о более высокой устойчивости энергосистемы к перебоям в поставках топлива. Такой же подход можно применить и к аналогичным показателям, которые измеряют возможности энергосистемы путем подсчета различных ее элементов.

*I*2. **Количество источников импорта электроэнергии**

Этот показатель связан с количеством межсистемных соединений, обеспечивающих электроэнергией энергосистему. Чем больше межсистемных соединений имеет энергосистема, тем выше ее устойчивость к внешним перебоям в снабжении. Показатель измеряется количеством (N) различных источников импорта электроэнергии. Показатель демонстрирует способность энергосистемы поглощать воздействие внешних перебоев в поставках (импорте электроэнергии). Однако происхождение источника импорта не учитывается при оценке устойчивости.

Для сравнения различных энергетических систем, как в случае с I1, этот показатель должен быть нормализован таким же образом:

*I*2 = *N*/*D*max · *U* (2)

где N - количество источников импорта электроэнергии.

***I3. Количество генераторов энергии***

Этот показатель измеряет количество (Ni) генераторов, производящих энергию, агрегированных по типу i, например, количество тепловых (угольных, нефтяных, газовых) электростанций, количество ветряных турбин или парков, или мощность солнечных установок. Количество генераторов также определяет объем генерирующих мощностей, которые подключаются для производства энергии в случае сбоев. Чем больше генераторов имеет энергосистема, тем более она устойчива к сбоям, например, к внеплановым отключениям генераторов. В случае перебоев в работе энергосистемы отдельным показателем может быть количество генераторов, расположенных в зоне, которая может пострадать от перебоев.

Для сравнения, как и в случаях I1 и I2, этот показатель должен быть связан с конкретной характеристикой энергосистемы:

*I*3 = *Ni*/*D*max · *U* (3)

где Ni - число генераторов типа i.

***I4. Мощность передающих трубопроводов***

В случае с природным газом, чем выше пропускная способность трубопроводов энергосистемы, тем больший объем природного газа может быть передан. Следовательно, трубопровод может также использоваться для краткосрочного хранения, что может покрыть поставки газа для производства электроэнергии. Высокая пропускная способность трубопроводов системы увеличивает возможности реагирования в случае перебоев в поставках, что приводит к повышению устойчивости энергосистемы. Пропускная способность газопроводов из различных источников рассчитывается как сумма мощностей всех газопроводов, входящих в энергосистему. Этот показатель измеряется в любой единице объема в единицу времени, например, м3/день или кВтч/день.

Однако для сравнения различных энергосистем или стран между собой этот показатель должен быть нормирован на потребление энергии за определенный период. Он может быть оценен как отношение общей мощности к потреблению (в процентах):

*I*4 = *TC*/*C* × 100% (4)

где TC - общая мощность передающих трубопроводов, а C - потребление энергии.

***I5. Пропускная способность линий электропередач***

# Способность энергетической системы повышать устойчивость зависит также от прочности межсистемных соединений и линий электропередачи. Эта прочность зависит как от количества линий электропередач, так и от их пропускной способности. Большая пропускная способность линий электропередачи указывает на более высокую способность снижать воздействие как внешних, так и внутренних сбоев.

# Этот показатель может быть измерен в любой единице энергетической мощности, например, в МВт или ГВт.

# Как и в случае с I4, для сравнения различных энергетических систем этот показатель необходимо нормализовать аналогичным образом, используя уравнение (4).

*I*6. **Длина магистральных трубопроводов**

Для природного газа, чем длиннее магистральные трубопроводы в энергетической системе, тем большее количество природного газа в них хранится. Эта характеристика энергетической системы известна как linepack, которая описывает общий объем природного газа, содержащегося в системе. Это обеспечивает альтернативные варианты на случай перебоев в поставках. Этот показатель измеряется в любой единице длины (L), например в километрах (км).

Как и в предыдущих случаях, для целей сравнения этот показатель необходимо нормализовать. Длина трубопроводов может быть связана, например, с максимальным спросом на электроэнергию. Этот показатель демонстрирует среднюю длину на единицу максимального спроса на электроэнергию:

*I*6 = *L*/*D*max · *U* (5)

где L - общая длина трубопроводов.

*I*7. **Длина линий передачи**

# Длину линий передачи в энергетической системе можно понимать как длину пути по этим линиям между различными узлами (например, производства и потребления). При большой длине пути сбой должен пройти через большее количество узлов и может быть устранен до того, как вся энергосистема выйдет из строя. Следовательно, более длинный путь (больше узлов между различными частями системы) приводит к замедлению сбоев в снабжении [43]. Этот фактор повышает устойчивость энергосистемы. Этот показатель может быть измерен в любой единице длины (L) (например, в км) или в количестве узлов между, например, производственными и потребительскими площадками. Показатель актуален как для внутренних, так и для внешних сбоев в электроснабжении. Для сравнения различных энергетических систем, как в случае с I6, этот показатель должен быть нормализован таким же образом.

# С другой стороны, длинные пути в обоих случаях (показатели I6 и I7) связаны с изначально более сложными энергетическими системами. Источник энергии находится дальше от места использования, и существует больше потенциальных точек отказа. В случае сбоя сложнее заменить вышедшую из строя деталь в экстренном порядке. Кроме того, малая длина пути позволяет легче управлять энергетической системой.

# *I*8. Number of connections in the energy system

This indicator represents the degree centrality of a node in the system where nodes represent intervention points. As stated in [43], the degree centrality of a node can be calculated by summing the connections that a node has to other components in the system. Central nodes (nodes with high centrality) allow for a quick stabilization of the energy system’s performance in the case of external or internal disruptions. This ability ensures higher energy system resilience. The energy system’s interconnections also increase resilience by providing alternative energy supply routes. This indicator reflects energy system structure with respect to production sites. The indicator may be measured as a count (*N*) of different connections to other producers or/and consumers in an energy system.

As in the cases above, to compare different energy systems, this indicator is normalized per unit of maximum electricity demand.

# *I*9. Configuration of the energy system

The energy system’s configuration may also increase energy system resilience. As stated in [47], configurations allow the energy system to be modified in case of failure of one or more nodes and arcs by opening and closing switches. Switches may be controlled manually, automatically, or remotely using supervisory control and data acquisition systems. In the case of disruption, energy system operators are able to divert power through other parts of the system. This indicator is measured as a percentage of node connections that are operated manually, automatically, and remotely:

*I*9 = *N*/*NTotal* × 100% (6)

where *N* is the number of node connections that are operated manually, automatically, and remotely and *NTotal* is the number of all node connections in the energy system. A higher indicator indicates higher energy system resilience.

Higher resilience should also be achieved when different system elements are not concentrated in one place but are in different locations within the system. For example, if most of the energy generators are located in one region of the energy system (e.g., on or near the coastline), it would reduce energy system resilience.

# *I*10. Modularity of the energy system

This indicator measures the autonomy of different parts of the energy system that function independently. As stated in [43], higher modularity allows for the autonomous functioning of the different parts of an energy system (e.g., islanding). Energy system resilience increases if the overall modularity or/and the clustering of a system increases. External and internal disruptions spread less quickly in modularized systems and can be

“blocked” at the entrance node to the module. This indicator is measured as a number (*N*) of independent distribution networks within the energy system.

To compare different energy systems, this indicator must be tied with a specific characteristic of the system. In this case, the proper characteristic is the total installed capacity. The indicator then would demonstrate the average number of independent distribution networks per unit of total installed capacity:

# *I*10 = *N*/*TIC* · *U* (7)

where *N* is the number of independent distribution networks in the energy system and *TIC*

is the total installed capacity.

## *I*11. Percentage of distributed energy technologies

Energy systems that are based on distributed energy have lower vulnerability in the case of power disruptions (e.g., loss of power at critical loads). This indicator measures the ability to maintain energy supply during disruptions. Distributed energy technologies might be used to supply energy and create redundancy in the energy system.

The indicator is expressed as a percentage in the following manner:

*I*11 = *NCF*/*NTotal* × 100% (8)

where *NCF* is the number of distributed energy technologies and *NTotal* is the number of all energy technologies in the energy system.

The higher this indicator, the higher the energy system resilience. However, for most energy systems today, distributed generation is not yet resolved, and this indicator may be more suitable for assessing the resilience of future energy systems.

## *I*12. Number of spare parts

This indicator measures the number (*Ni*) of spare parts of type *i* an electric utility has on hand in the presence of disruption. It demonstrates the capabilities of the companies operating the systems through the maintenance of spare equipment (e.g., transformers, switches, cables) for rapid repair to absorb the impacts of disruption. A higher indicator demonstrates higher energy system resilience. However, the availability of spares usually depends on cost. For instance, electric power utilities often maintain small stocks of relatively inexpensive equipment for maintenance and emergencies. Some of the spare parts are difficult to maintain because of their high cost and specificity [47]. Thus, just having a larger number of spare parts necessarily increases resilience meaningfully. This number has to be tied with projected needs for these spare parts in the case of disruption. In this case, not only the number of spare parts has to be taken into account, but also the total number of parts that might be damaged and potentially need to be replaced in the case of disruption:

*I*11 = *Ni*/*NTotal* × 100% (9)

where *Ni* is the number of spare parts of type *i* and *NTotal* is the total number of parts that might be damaged in the case of disruption.

## *I*13. Diversity indicators

Diversity allows for the use alternative energy technology instead of the technology that has been disrupted. Many diversity indicators exist in the scientific literature, for example, in [48]. In this paper, diversity indicators are divided into three groups according to which type of energy chain in the energy system is measured: (1) energy supply, (2) energy production, and (3) energy installation.

1. Diversity of primary energy sources or fuels

This indicator demonstrates the diversity of the supply of primary energy sources

(PES) or fuels used in energy production. It should be evaluated for particular PES or fuels such as coal, oil, natural gas, and biomass. Imported and domestic fuels can be aggregated into a single group. Diversification in the supply of PES or fuels should make an energy system more resilient in case the supply of a particular PES or fuel is missing. This indicator measures energy system resilience against various PES or fuel supply disruptions.

1. Diversity in the energy production mix

The indicator demonstrates the level of dependency of one energy production technology in total energy production. Energy import technology also should be included as a separate technology in satisfying energy demand. High diversity in the energy generation mix ensures higher resilience in the case of one or other energy production technology is lost. This indicator relates to both internal and external disruptions.

1. Diversity in installed energy capacity

This indicator demonstrates the diversification of installed capacity from different fuel sources that may be used to produce energy. The indicator measures the potential energy production. The more options an energy system has, the higher its resilience.

In this paper, the three groups of the above-described diversity indicators are measured in three different ways.

1. Number of energy supply, production and installed energy technologies

Energy technologies are divided according to different energy diversity indicators discussed above:

(1) PES or fuels; (2) energy production; (3) installed capacity.

In this case, the indicator is evaluated by counting different energy technologies and is measured only by category count:

*I*13*a* = *Ni* (10)

where *i* represents three different energy technologies (*i* = 1, 2, 3), *N*1 is the number of PES or fuels in energy supply, *N*2 is the number of energy production technologies in energy production, and *N*3 is the number of energy technologies in installed capacity.

The number of different energy technologies existing in the energy system shows the variety in energy supply, production, and installed capacity. The impact of this indicator is twofold: if the energy system shows low variety, it is more stable; however, in the case of disruption, such an energy system might not react properly due to lower capacity.

1. Share of energy supply, production and installed energy technologies

This indicator demonstrates what share is covered by one energy technology, for example, in energy supply, the energy production mix or installed capacity. The high use of one technology increases the dependency in the energy supply, which exposes the energy system to potential disruptions in supply.

In this case, the indicator is calculated as follows:

*I*13*b* Изображение выглядит как черный, темнота

Автоматически созданное описание100% (11)

where *Si*1 is the amount of supply of PES or fuel *i*, *Si*2 is the amount of energy produced from the energy production technology *i*, *Si*3 is installed capacity of energy technology *i*, and *n* is the total number of energy technologies.

This indicator measures diversity in the energy system from the dominance/distribution of one energy technology point of view. In general, a high share of one energy technology indicates low energy system resilience. This case refers to the balance of different energy technologies. A high balance is reached when energy technologies in the energy system are distributed evenly and potentially implies a higher degree of flexibility, which again reflects higher resilience. A low balance leads to lower resilience and is reached when energy supply or production is concentrated on one or a just a few energy technologies.

(c) Diversity indicators (SWI and HHI)

Balance across different energy technologies within the energy system is measured by the Shannon-Wiener index (SWI) or the Herfindahl-Hirschman index (HHI), which are widely used in the scientific literature [49–51]. Both indicators are expressed in numeric values based on the shares of energy technologies in the energy system. These indicators measure the balance and diversity in energy supply, energy production, and installed capacity. SWI and HHI indicate whether one energy technology is dominant or not in the energy system.

SWI is calculated as follows:

SWI Изображение выглядит как черный, темнота

Автоматически созданное описание (12)

where *p*1*i* is the share of PES or fuel *i* in the total supply, *p*2*i* is the share of energy production technology *i* in the total energy production, and *p*3*i* is the share of energy technology *i* in the total installed capacity.

If only one energy technology option is available, SWI is equal to zero. By contrast, if energy technology shares are even, SWI reaches a theoretical maximum that depends on the number of energy technologies in the energy system. In order to have limits for SWI, it can be normalized in the following way:

SWI*norm* Изображение выглядит как черный, темнота

Автоматически созданное описание *n* (13)

The normalized SWI is between 0 and 1. In both cases, the higher the SWI, the higher the diversity, which indicates higher energy system resilience.

HHI demonstrates the concentration of the individual shares of the energy technologies in the energy system. It is calculated as follows:

HHI Изображение выглядит как черный, темнота

Автоматически созданное описание (14)

where *pik* is expressed as a percentage.

The lower the HHI, the greater the diversity, again indicating higher energy system resilience. The minimum value is reached when all the shares are equal.

## *I*14. Largest single source of energy supply/production

This indicator is measured as a share of the largest energy supply or production of one technology in the total energy supply or production. The supply term includes not only energy production but also energy import in order to satisfy the energy demand. This indicator is expressed as a percentage of supply/production in the following manner:

*I*14 = *SL*/*ST* × 100% (15)

where *SL* is the amount of the largest energy supply/production of one technology, *ST* is the amount of the total energy supply/production in the energy system.

If the share of one energy technology is dominant in the energy supply or production, the energy system is vulnerable to energy supply disruptions. A higher indicator demonstrates higher vulnerability and less energy system resilience.

## *I*15. Import dependency

One way to define this indicator is the share of energy import in the total energy demand. The indicator is evaluated as one minus the ratio between energy production and energy demand (as a percentage):

*I*15*a* = (1 − *P*/*D*) × 100%, (16)

where *P* is the amount of the produced energy and *D* is the energy demand.

A higher indicator indicates higher dependency on energy imports and thus less energy system resilience.

Another way to evaluate this indicator is the ratio between energy demand and energy production:

*I*15*b* = *D*/*P* (17)

If the indicator is lower than 1 (production > consumption), the energy system has energy export capabilities. This represents a more resilient energy system. However, if the indicator is higher than 1 (consumption > production), the energy system is dependent on energy imports, and high import dependency makes the energy system more vulnerable to external supply disruptions, that is, less resilient.

## *I*16. Share of renewable energy sources in energy production

This indicator defines the use of energy from nonfossil energy carriers in energy production. The availability of renewable energy sources (RES) depends on the analyzed energy system and can include hydropower, wind, solar, biomass, geothermal, and other sources, e.g., tides and waves.

This indicator is evaluated as the RES share in the energy production as a percentage, and calculation is based on the ratio of energy production from RES to the total energy production:

*I*16 = *PRES*/*P* × 100% (18)

where *PRES* is the amount of energy production from RES.

A diversified energy mix is one way to increase energy system resilience. The use of renewable energy may offset the vulnerability coming from high import levels of fossil fuels. Small hydro systems may reduce the need for extensive transmission and distribution lines, which may generate new vulnerabilities. Wind, solar, and local biofuel technologies allow for energy generation from the local resources. Thus, the more RES is used as a share of the total energy production, the less vulnerable the energy system is to supply disruptions, which indicates higher resilience. However, if the penetration of RES is too deep and no proper balancing and storage options are available, energy system resilience might be lower as well due to the risk of blackout.

## *I*17. Energy reserves

One way to evaluate this indicator is to calculate the reserves to production ratio as a percentage:

*I*17 = *ST*/*P* × 100% (19)

where *ST* is the capacity of storage/reserves.

Another way to measure the indicator is in the length of time (e.g., days, years). The indicator then gives the period for which the available reserves can be used for energy production. In both cases, a higher indicator reflects higher energy system resilience. The impact of disruption on reserves is heavily dependent on the amount of energy stored at the time of the disruption.

## *I*18. Spare capacity

This indicator measures the difference between the amount of energy produced in a unit of time (e.g., hours) and the amount of energy that could be produced at full capacity:

*I*Изображение выглядит как черный, темнота

Автоматически созданное описание (20)

where *ICi* is installed capacity of energy technology *i*, *t* is time in hours (*t* = 8760 h on a yearly basis), *CFi* is the capacity of the energy technology *i*, *Pi* is the amount of energy of produced by the energy technology *i*, and *n* is the number of energy technologies in the energy system.

This indicator demonstrates the ability of the energy system to produce more energy than is now being produced (if necessary). A higher indicator demonstrates higher energy system resilience to supply disruptions.

## *I*19. Ratio of total installed capacity to energy demand

This indicator is measured as the ratio between the available generation capacity and the energy demand. If the electricity system is analyzed, generation capacity might include not only electricity generators but connection lines (interconnectors) as well.

Calculation of the indicator is based on a ratio of the total installed capacity to the total energy demand:

*I*19 = *TIC*/*D* × 100% (21)

This indicator addresses the energy system’s excess generation capacity. High installed capacity demonstrates the energy system’s capability of absorbing the impact of internal disruptions and satisfying the demand. A higher indicator reflects higher energy system resilience.

## *I*20. Energy cost stability

The prices of traditional fossil fuels are more volatile than the prices of RES. As the energy system (especially the electricity system) might be particularly vulnerable to these price fluctuations due to various factors, the stability of energy cost should be taken into consideration.

This indicator measures the stability of energy technology costs of electricity generation against energy or fuel price fluctuations. The calculation of the indicator is based on the fraction of energy or fuel cost to the energy technology costs of electricity generation (expressed as a percentage):

*I*20 = *EC*/*TC* × 100% (22)

where *EC* is the energy or fuel cost and *TC* is the energy technology cost of electricity generation.

This indicator is specifically relevant in the case of cost shocks in the energy system.

Greater fluctuation in the indicator reflects lower energy system resilience.

## *I*21. Energy demand

Reduced energy demand allows for reducing dependence on imports and decreasing expenditures on energy. However, the increase in energy demand due to extreme cold or hot weather might lead the energy system to disruptions. Less volatile energy demand leads to higher energy system resilience. Moreover, the higher the growth of energy demand, the less has been achieved in reducing vulnerability to supply disruptions.

### *2.2. Performance-Based Indicators*

Indicators discussed in Section 2.1. mostly measure the energy system’s capacity to absorb or limit the impacts of disruption. Some of these indicators (e.g., import dependency, RES share, diversity) show the changes in the energy system during the disruption. Thus, some indicators can measure the performance of the energy system in the presence of disruption and demonstrate the level of energy system resilience. Some quantitative indicators to measure the performance of the energy system in the case of a sudden shock are proposed further (the numbering of indicators is continuing).

## *I*22. Unserved energy

Unserved energy or energy not supplied can be described as an estimate of the energy that would otherwise have been used by customers but for disruption. The level of unserved energy can be evaluated either in a quantitative amount (e.g., PJ or GWh) or in percentage (%).

Based on [6,52], the first indicates how much energy was not provided during the studied time period as an absolute number. The second case is directly related to the first and is normalized using the energy demand in the studied time frame or on a yearly basis and expressed as a percentage:

*I*22*a* = *UE*/*D* × 100% (23)

where *UE* is the amount of unserved energy.

This indicator as a percentage can also be calculated in another way using the energy supply and energy demand variables:

*I*22*b* = (1 − *S*/*D*) × 100% (24)

where *S* is the amount of the supplied energy.

This performance-based indicator describes the impacts of energy supply disruptions on the performance of the energy system. A higher indicator indicates lower energy system resilience.

## *I*23. Time of unserved energy

Time of unserved energy can be measured in any unit of time per a certain timeframe

(e.g., hours per year) or in the percentage of the time energy that is unserved per a certain timeframe. For example, the second measure on yearly basis can be calculated as follows:

*I*23 = *TUE*/8760 × 100% (25)

where *TUE* is the number of hours in which energy demand is not met in a year.

This indicator is relevant in the case of supply disruptions. A higher indicator demonstrates lower energy system resilience.

## *I*24. Cost change

This indicator is used to evaluate the impacts of both supply and cost disruptions. This performance-based indicator defines changes (in most cases increases) in the energy system’s total costs compared with the costs of the reference case (no disruptions). The total discounted cost of the energy system is the result of the objective function of most of the energy system optimization models.

As suggested in [52], energy cost change is based on the total discounted cost in the case of a disruption scenario and cost in the case of the reference scenario. The percentage of energy cost change is calculated in the following manner:

*I*24 = ((*SC* − *BC)*/*BC*) × 100% (26)

where *BC* is the total cost of the scenario without disruptions and S*C* is the total cost of the scenario with disruptions.

This indicator reflects the percentage that a certain disruption changed (increased or decreased) the total discounted costs of the energy system. If the value is positive, the costs increased, and if the value is negative, the costs decreased. If the value is zero, the costs were not changed. A higher positive indicator indicates lower energy system resilience to cost and supply disruptions.

The above discussed performance-based indicators measure energy system resilience to various disruptions and demonstrate the system’s performance in the presence of these disruptions.

The proposed indicator framework in Section 2 can also be applied to prospective energy systems including estimating the resilience against future disruptions. For estimating most resilience indicators, the energy system model, which models energy system development in the future, is needed. However, not all discussed resilience indicators can be evaluated from the results of energy system models. The evaluation of future foresight capabilities of such indicators should be performed from either statistical data (forecasts) or other detailed data from, for example, energy network models.

In the next sections, the performance of selected resilience indicators in the future perspective is demonstrated by conducting a modeling exercise using the energy system of Lithuania.

### 3. Energy System Model

В этом разделе описывается модель энергетической системы и основные допущения моделирования. Моделирование проводится для того, чтобы продемонстрировать эффективность индикаторов энергетической устойчивости для различных сценариев, которые представляют собой будущие сценарии развития энергетической системы. В основном оно основано на подробном техническом и экономическом анализе будущих показателей энергосистемы Литвы. Далее кратко описывается структура модели, используемые инструменты, ключевые допущения моделирования и сценарии.

3.1. *Инструмент для моделирования энергетических систем*

Основным этапом работы демонстрационного примера и оценки показателей устойчивости является моделирование энергетической системы. В исследовании используется подход долгосрочного моделирования энергосистемы, который позволяет оценить показатели устойчивости на будущее. В данном исследовании модель энергетической системы Литвы построена с использованием системы моделирования энергетики с открытым исходным кодом (OSe Source Energy Modeling System).

Система энергетического моделирования с открытым исходным кодом (OSeMOSYS). Это инструмент, разработанный Королевским технологическим институтом KTH в сотрудничестве с рядом других учреждений. Целевая функция OSeMOSYS заключается в минимизации общих дисконтированных затрат на энергетическую систему для удовлетворения заданного спроса на энергетические услуги, который может быть удовлетворен с помощью ряда технологий. Более подробное описание и реализацию инструмента OSeMOSYS можно найти в [53,54].

Для разработки модели энергетической системы Литвы и оценки показателей устойчивости необходимо сделать исходные предположения, которые могут оказать существенное влияние на саму модель и результаты смоделированных сценариев.

#### 3.2. Model Structure and Key Modeling Assumptions

В данном демонстрационном примере структура модели основана на модели MESCA (Model for Energy Security Coefficient Assessment), которая была разработана в ходе реализации проекта Европейской комиссии REEEM [55] и более подробно описана в [56]. В математической модели энергетической системы основное внимание уделяется системе электроснабжения. Однако система централизованного теплоснабжения в Литве связана с электроэнергетической системой с помощью теплоэлектростанций.

Энергетическая система в модели представлена системами топливообеспечения, электроснабжения, производства и подачи тепла. Она также характеризуется существующими и планируемыми технологиями, такими как электростанции, тепловые котлы, сети передачи и распределения, местное и импортное топливо, а также импорт электроэнергии. Каждая технология характеризуется техническими и экономическими параметрами, например, эффективностью, сроком службы, установленной мощностью и стоимостью.

Период анализа - с 2015 по 2050 год с шагом в 1 год. Каждый год в модели разделен на 15 временных срезов, которые представляют собой 5 сезонов и 1 типичный день в каждом сезоне: ночь, день и пик. Этот подход применяется в модели OSeMBE (Open Source Energy Model Base for the European Union) [57], которая является одним из основных приложений инструмента OSeMOSYS. Такое разделение на временные срезы одновременно отражает среднюю электрическую нагрузку и переменную генерацию ветра. Использовался коэффициент дисконтирования 5%. В модель также включены уже реализованные и прогнозируемые крупные инфраструктурные проекты энергосистемы, например, энергетические и газовые межсистемные соединения с соседними странами.

#### 3.3. Data

Период анализа - с 2015 по 2050 год с шагом в 1 год. Каждый год в модели разделен на 15 временных срезов, которые представляют собой 5 сезонов и 1 типичный день в каждом сезоне: ночь, день и пик. Этот подход применяется в модели OSeMBE (Open Source Energy Model Base for the European Union) [57], которая является одним из основных приложений инструмента OSeMOSYS. Такое разделение на временные срезы одновременно отражает среднюю электрическую нагрузку и переменную генерацию ветра. Использовался коэффициент дисконтирования 5%. В модель также включены уже реализованные и прогнозируемые крупные инфраструктурные проекты энергосистемы, например, энергетические и газовые межсистемные соединения с соседними странами.

#### 3.4. Scenarios

Сценарии, использованные в данном упражнении, были построены в соответствии с предположениями о базовом и высоком уровнях использования ВИЭ, разработанными в рамках проекта REEEM и представленными в Первом отчете о комплексном воздействии [61]. Оба сценария основаны на переходе энергетической системы к низкоуглеродному энергетическому будущему.

The main factors defining energy system scenarios are emissions of greenhouse gases

(GHG) and the use of RES. It was assumed that GHG emissions in the emission trading sector (ETS) should be reduced by 21% in 2020, by 43% in 2030, and by 83% in 2050 compared to the 2005 emission levels. However, the GHG emission targets for non-ETS are set as +15% in 2020, −9% in 2030, and −60% in 2050. These targets demonstrate that emission increase at the beginning of the study period is allowed.

Another factor used for scenarios assumptions is the national RES targets. The existing targets of renewable share in gross final consumption for Lithuania in the base case are 23% in 2020, 36% in 2030, 56% in 2030, and 75% in 2050. Assumptions for the GHG emission and renewable energy targets are based on the EU 2020 Climate and Energy Package [62], the 2030 Climate and Energy Framework [63], and the EU Roadmap 2050 [64] and are in line with the Paris Agreement [65].

In general, the base and high RES scenarios did not demonstrate significantly different results, and therefore, additional assumptions for both scenarios were introduced and adopted in this study. Two scenarios are considered: Scenario 1 (SC1), which corresponds to the base pathway and represents current energy system trends, and Scenario 2 (SC2), which corresponds to the high RES pathway that assumes higher renewable energy generation targets.

Since the focus of the study is on the electricity system, RES share targets are applied for final electricity consumption and are modified for the analyzed scenarios. We added an assumption regarding the constraint for electricity import. It is assumed that electricity imports over time will be replaced by local electricity generation, which should reach a certain share. The assumed targets for the use of RES and the share of local electricity generation in the country are presented in Table 1.

**Table 1.** Shares of RES in the final electricity consumption and local electricity generation.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Scenario** | **Type of Share** | **2020** | **2030** | **2040** | **2050** |
| SC1 (Base) | Share of RES Share of generation | 23%  20% | 36%  50% | 56%  65% | 75%  80% |
| SC2 (High RES) | Share of RES Share of generation | 30%  35% | 45%  70% | 72.5% 85% | 100%  100% |

Assumptions for SC2 correspond to the outlined objectives in the National Energy Independence Strategy of the Republic of Lithuania [66].

## Hypothetical disruptions in the energy system

The main goal of most resilience indicators is to evaluate energy system performance in the case of disruptions or shocks and investigate the impacts. Disruptions in the energy system might occur for different reasons, for example, failures or unplanned outages of technical equipment, weather-related events, volatility in global energy prices, or attacks (both physical and cyber) on energy infrastructure. All these events usually affect the energy system in two ways: interruption of energy supply sources and energy price shocks. In this paper, the focus is on these types of disruptions that might have an impact on the energy system.

In order to demonstrate the performance of resilience indicators for the future, constructed scenarios (SC1 and SC2) must be also modeled in the case of certain disruptions (shocks). Therefore, additional disruption scenarios have been developed for this purpose.

In contrast to reliability, resilience usually is associated with long-duration power disruptions caused by high-impact and low-probability events. Here, some disruptions to the electricity system are hypothesized as separate scenarios, and the long-term impacts to the energy system with the selected resilience indicators are investigated. In order to compare the results of the analyzed scenarios, it is assumed that these disruptions occur in the same time frame, from 2025 to 2035, under each of the two analyzed scenarios. The analyzed disruption scenarios are the following:

D1. The loss of energy import sources;

D2. The loss of natural gas supply;

D3. The loss of biomass supply;

D4. The loss of wind PPs (both onshore and offshore) in electricity production.

Such extreme hypothetical disruption scenarios were selected for purposes of demonstrating the long-term performance of the resilience indicators for the future.

### 4. Modeling Results

The modeling exercise was performed using the energy system model described in

Section 3. First, the energy system model was run in the case of two scenarios (SC1 and SC2) without any disruptions in the system. This was to demonstrate how the energy system might develop under certain assumptions and constraints in the future. It should be emphasized that this is not a forecast but a hypothetical development of the energy system under different assumptions within different scenarios. Then, each of the scenarios is run under different disruption scenarios as introduced in Section 3.4. Selected resilience indicators are evaluated for these scenarios and the results provided.

#### 4.1. Installed Capacity and Electricity Production

Among the main results are the electricity production mix and the installed capacities in each analyzed scenario. These results may highly affect the performance of the energy system in the case of various disruptions, and the performance will be measured with resilience indicators. The results of the installed capacities of power plants and their interconnectors as well as the electricity production in Lithuania in the analyzed scenarios are presented in Figure 1.

Изображение выглядит как снимок экрана, Красочность, Графическое программное обеспечение

Автоматически созданное описание

**Figure 1.** (**a**) Installed capacities of electricity production sources; (**b**) electricity production by different energy technologies.

The largest shares of installed capacity of power plants at the beginning of the study period come from natural gas (52%), hydro (28%), and wind (10%) in both scenarios. Over time, the installed capacities of fossil fuel-fired plants decrease, and capacities of

RES increase significantly. At the end of the analysis period, the largest share has wind

(approx. 50% in both scenarios) with the contributions of biomass, hydro, solar, and natural gas. However, these shares have slightly different results among scenarios; for example, solar and biomass have higher shares in SC2, and natural gas has higher share in SC1. Furthermore, the total installed capacity in 2050 is higher by 4% in SC2 in comparison with SC1.

Electricity imports at the beginning of the study period are a dominant source of electricity supply. The share of imported electricity covers 60–70% of the total electricity requirement in Lithuania in both scenarios until 2020. Due to assumptions in both scenarios, electricity imports decrease significantly over time, mostly replaced by wind energy, biomass technologies, and some solar at the end of the study period.

A faster decline in electricity imports and a faster increase in RES is observed in SC2, in which assumed targets were more ambitious regarding RES than in SC1. Electricity production from wind and biomass is growing in time to compensate for electricity import reductions. Thus, the share of wind energy in electricity production in 2030 reaches 23% in SC1 and 40% in SC2; in 2050 the share excels at approx. 57% in both scenarios.

The penetration of RES technologies over time changes the diversity in the energy system and the type of the largest share in the electricity mix. In SC1, electricity imports decrease to 54% by 2030 and wind attains 57% by 2050. In SC2, wind energy attains 40% by 2030 and 56% by 2050, having the largest share. The modeling of the energy system is also performed in the case of various disruptions (both supply and cost shocks), which were introduced and discussed in more detail in Section 3.4.

#### 4.2. Resilience Indicators under Hypothetical Disruptions in the Energy System

Several disruptions to the Lithuanian energy system that might have an impact on electricity supply were hypothesized under analyzed scenarios. In order to demonstrate the performance of the energy system under these disruptions, several resilience indicators were selected and evaluated: (a) unserved energy (*I*22); (b) cost change (*I*24); (c) import dependency (*I*15); (d) share of RES (*I*16); and (e) the diversity indicators (*I*13) (SWI and HHI). However, the results present the estimates only of these indicators, which demonstrate some changes in the energy system due to disruptions.

4.2.1. The Loss of Electricity Import Sources (D1)

In this disruption scenario, the loss of all five electricity import sources (differentiated by import country) in the Lithuanian energy system was considered. First, the unserved energy indicator was observed (Figure 2), which indicates the percentage of electricity import needed for the energy system to “survive” (to avoid unserved energy).

This indicator is demonstrated only during the time period of disruption. Higher impact of the disruption and lower energy system resilience are seen in SC1, which is more dependent on electricity imports in comparison with SC2. In SC1, 23% of electricity imports is needed for the energy system to avoid unserved energy in 2025, whereas the value in SC2 is 8% at the same time. However, the indicators in both scenarios decrease with the decreasing dependency on electricity import. The energy system can survive without electricity imports from 2029 in SC2 and from 2034 in SC1.

In 2025, the share of electricity imports in the electricity supply still covers the largest proportion in both scenarios without disruptions, 62.5% in SC1 and 47.5% in SC2. This is estimated by the import dependency indicator, presented in Figure 3. Obviously, the values of this indicator should not be taken into account during disruption scenarios (SC1\_D1 and SC2\_D1) when all electricity import sources are lost and indicators are equal to 0.

0

5

10

15

20

25

Unserved energy (

%)

1. 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035

Year

SC1 SC2

**Figure 2.** Unserved energy (%) in the case of the loss of all electricity import sources.

0

10

20

30

40

50

60

70

80

2015

2020

2025

2030

2035

2040

2045

2050

Import dependence (%)

Year

SC1 SC2 SC1\_D1 SC2\_D1

**Figure 3.** Import dependence (%) in the case of the loss of all electricity import sources.

Change in energy system total costs was also evaluated during the disruption time frame (Figure 4). Over time, the indicators increase since relatively cheaper electricity imports are replaced due to unavailability with technologies that produce electricity at higher costs.

0

5

10

15

20

25

30

35

Cost change

(

%)

1. 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035

Year

SC1 SC2

**Figure 4.** Cost change (%) in the case of the loss of all electricity import sources.

SC1 demonstrates less resilience to cost changes than SC2 when all electricity import sources are lost. In 2035, SC1 demonstrates an increase of ~33%, and in SC2, the increase is ~18% at the same time.

The results for the estimated indicators demonstrate that over time, the analyzed energy system tends to be more resilient to disruptions related to the loss of electricity imports. In both analyzed scenarios, a decrease in dependency on electricity imports is observed, and SC2 performs better since it assumes higher RES targets and is less dependent on electricity imports in comparison with SC1.

4.2.2. The Loss of Natural Gas Supply (D2)

In this disruption scenario, the complete loss of natural gas supply for energy production is considered. In SC1 and SC2, electricity from natural gas is produced until 2030 (due to constraints on RES targets), and the share has a decreasing trend; therefore, this disruption does not significantly change the electricity mix. The shares of natural gas in electricity production in 2025 are approx. 2.1% in SC1 and 2.6% in SC2. The lost portion of natural gas for electricity production is simply replaced by electricity imports in the case of disruption from 2025. Unserved energy during the disruption period is not observed, and the change in total costs of the energy system reached a maximum value of 0.5% and is not analyzed in more detail.

The estimates of these two indicators demonstrate high energy system resilience in both scenarios in the case of the loss of natural gas supply. However, this observation is applied only to the electricity system. The heating system is more impacted by this disruption, but details are not analyzed since it is out of the scope of this study.

Figure 5 shows the import dependency indicator, which in the case of the loss of natural gas supply demonstrates that the energy system relies more on electricity imports during the disruption period. However, the difference is not significant since over time, the energy system in both scenarios is decreasingly dependent on electricity production from natural gas.

20

25

30

35

40

45

50

55

60

65

70

Import dependence (%)

2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035

Year

SC1 SC2 SC1\_D2 SC2\_D2

**Figure 5.** Import dependence (%) in the case of the loss of natural gas supply.

Import dependence is decreasing due to constraints in both scenarios on electricity production in the country. In addition, these constraints are neglected in the case of a shock to let the energy system absorb the impact first, but this is not necessary to fulfill the requirement due to certain targets set in both scenarios.

The diversity indicators (SWI and HHI) in Figure 6 show a better balance across different energy production technologies in electricity production in scenarios without disruption.

1

1.05

1.1

1.15

1.2

1.25

1.3

1.35

1.4

1.45

2024

2025

2026

2027

2028

2029

2030

2031

2032

2033

2034

2035

SWI

Year

SC1

SC2

SC1\_D2

SC2\_D2

2500

3000

3500

4000

4500

5000

2024

2025

2026

2027

2028

2029

2030

2031

2032

2033

2034

2035

HHI

Year

SC1

SC2

SC1\_D2

SC2\_D2

## (a) (b)

**Figure 6.** Diversity indicators in the case of the loss of natural gas supply: (**a**) SWI; (**b**) HHI.

During the shock phase, less diversification is observed due to the loss of one energy production technology in electricity production. SC2 performs better (SWI higher, HHI lower) in terms of diversity at the beginning of the analyzed period in comparison with SC1. Over time, the share of electricity imports is decreasing, which results in better performance of the diversification indicators; however, the share of wind PP is increasing and comprises a large portion at the end of the period, which results in a lower balance of electricity production in SC2 than in SC1.

In general, the results for the resilience indicators in both scenarios demonstrate the high resiliency of the electricity system to the loss of natural gas supply during 2025–2035.

4.2.3. The Loss of Biomass Supply (D3)

In this disruption scenario, the complete loss of biomass supply for energy production is analyzed. SC1 and SC2 in the period of disruption are more dependent on biomass supply than on natural gas supply. The maximum share of biomass in electricity production during the analyzed period is approx. 21% in SC1 (reached in 2026) and 25% in SC2 (reached in 2027). Later, these shares in both scenarios decrease because wind energy rapidly penetrates the energy system and takes the role of the largest share from electricity imports.

The lost portion of biomass for electricity production at the beginning of the disruption period (2025–2029) is mostly replaced by natural gas. By 2030, electricity imports overtake the lost portion of biomass in the electricity supply with a higher share in SC1. Unserved electricity during the disruption period is not observed in this case. The change in total costs of the energy system during the disruption time frame is presented in Figure 7.

The largest increase in costs is observed at the beginning of the period when the share of biomass in electricity production reaches its peak. Biomass technologies due to unavailability to produce electricity are replaced with technologies that produce electricity at higher cost. However, over time, the indicators decrease, and the cost increase is lower when the electricity system is less dependent on biomass supply. SC2 demonstrates less resilience to cost changes than SC1 when biomass supply is lost. In 2035, cost increases by 12% in SC1 and by 13% in SC2, with averages of almost 20% and 21% for SC1 and SC2, respectively (Figure 7).

These results do not contradict the scenario assumptions in which SC2 has higher RES targets. The performance of the RES share in the electricity production and import dependency during the disruption phase is presented in Figure 8.

0

5

10

15

20

25

30

2025

2026

2027

2028

2029

2030

2031

2032

2033

2034

2035

Cost change

(

%)

Year

SC1 SC2

**Figure 7.** Cost change (%) in the case of the loss of biomass supply.

10

20

30

40

50

60

70

80

2024

2025

2026

2027

2028

2029

2030

2031

2032

2033

2034

2035

RES

share

%

(

)

Year

20

30

40

50

60

70

80

2024

2025

2026

2027

2028

2029

2030

2031

2032

2033

2034

2035

Import dependence (%)

Year

SC1 SC2 SC1\_D3 SC2\_D3 SC1 SC2 SC1\_D3 SC2\_D3

## (a) (b)

**Figure 8.** Resilience indicators in the case of the loss of biomass supply: (**a**) RES share; (**b**) import dependence.

In 2025, when the sudden loss of biomass supply occurs, the share of RES in the electricity production drops by 20 percentage points (from 35% to 15%) in SC1 and by 19 percentage points (from 47% to 28%) in SC2 (Figure 8a). This difference until the end of the disruption remains at a similar level. The loss of biomass supply leads to noncompliance with RES obligations that were implemented as constraints in energy systems without disruption. The energy system is not able to maintain the same level of RES due to the disruption.

Electricity import dependence has two sudden upturns in 2025 and 2030 (Figure 8b). The reason for the first is that the lost portion of biomass for electricity production is mostly replaced by natural gas and some by electricity imports. In 2030, electricity from natural gas is no longer produced, and its full share is replaced by electricity imports, which largely results in increased dependency on imports.

The results of these indicators are also reflected in the diversification indicators. The high share of electricity imports results in the low performance of the SWI and HHI indicators during the disruption period (Figure 9). For example, dependency on electricity imports in SC1 reaches even 70%, which reflects a poor balance in the electricity supply.

0.7

0.8

0.9

1

1.1

1.2

1.3

1.4

1.5

2024

2025

2026

2027

2028

2029

2030

2031

2032

2033

2034

2035

SWI

Year

SC1

SC2

SC1\_D3

SC2\_D3

2500

3000

3500

4000

4500

5000

5500

6000

2024

2025

2026

2027

2028

2029

2030

2031

2032

2033

2034

2035

HHI

Year

SC1

SC2

SC1\_D3

SC2\_D3

## (a) (b)

**Figure 9.** Diversity indicators in the case of the loss of biomass supply: (**a**) SWI; (**b**) HHI.

The results for the estimated indicators demonstrate that SC1 is more resilient to the loss of biomass supply in comparison with SC2. However, the resilience in both scenarios over time increases with the decreasing share of biomass in electricity production. It has been also shown that the RES share targets and targets for the share of electricity generation in the country that were assumed in the scenarios were not fulfilled; instead, the energy system had to cover electricity production with other technologies such as natural gas and electricity imports.

4.2.4. The Loss of Wind Generators (D4)

The complete loss of wind PPs (both onshore and offshore) is considered in this disruption scenario. SC2 during the disruption period is much more dependent on electricity production of wind technologies in comparison with SC1. The share of wind energy in electricity production during this period increases from 7% to 37% in SC1 and from 19% to 52% in SC2. After the disruption period, this share increases further since wind energy shows excellent penetration into the energy system to fulfill the RES targets we set as scenario assumptions.

The lost share of wind energy for electricity production is mostly replaced by electricity imports. Unserved electricity during the disruption period is not observed. The change in total costs of the energy system was estimated during the disruption time frame and is presented in Figure 10.

This indicator results in an opposite effect in comparison with the loss of biomass supply. The largest increase in costs is observed at the end of the period, when the share of wind energy in electricity production is much higher. The cost change indicator in SC2 demonstrates less resilience to the loss of wind PPs in comparison with SC1. The highest values are observed in 2034 in both scenarios, 21% in SC1 and 31% in SC2 (Figure 10).

RES share, import dependence, and the diversity indicators reveal changes in the energy system under this disruption as well. In 2025, when electricity production from wind PPs is lost, the share of RES is diminished by 6 percentage points (from 35% to 29%) in SC1 and by 17 percentage points (from 47% to 30%) in SC2 (Figure 11a). RES share during the disruption does not exceed 29% in SC1 and 33% in SC2. The sudden shock has a higher impact on the energy system in SC2 since the differences in RES share in the cases with and without disruption are significantly higher in comparison with SC1.

0

5

10

15

20

25

30

35

2025

2026

2027

2028

2029

2030

2031

2032

2033

2034

2035

Cost change

(

%)

Year

SC1 SC2

**Figure 10.** Cost change (%) in the case of the loss of wind generators.

20

30

40

50

60

70

80

2024

2025

2026

2027

2028

2029

2030

2031

2032

2033

2034

2035

RES

share

%

(

)

Year

20

30

40

50

60

70

80

2024

2025

2026

2027

2028

2029

2030

2031

2032

2033

2034

2035

Import dependence (%)

Year

SC1 SC2 SC1\_D4 SC2\_D4 SC1 SC2 SC1\_D4 SC2\_D4

## (a) (b)

**Figure 11.** Resilience indicators in the case of the loss of wind generators: (**a**) RES share; (**b**) import dependence.

The indicator of the import dependency confirms that in the case of disruption, most wind energy is being replaced by electricity imports (Figure 11b). During the disruption period, the share of electricity imports is increasing and observes maximum values of 79% in SC1 and 75% in SC2, which are much higher than of those scenarios without disruption.

The diversity indicators in Figure 12 demonstrate significant changes in the balance across different electricity production technologies in the case of disruption.

The loss of wind energy in electricity production also shows less diversification. A significant increase in import dependency results in a low balance across technologies. Both these effects reduce the good performance of the diversity indicators during the disruption phase. In 2030, the electricity from natural gas is no longer produced and thus has an impact on the diversification of the energy system.

The results for the estimated indicators demonstrate that SC1 has higher resilience to the loss of the wind PPs in electricity production in comparison with SC2. In addition, the performance of both scenarios in terms of energy system resilience to the analyzed disruption over time decreases slightly. The main reason for that is that the energy system over time has to fulfill the RES requirements and production targets, which makes the electricity production highly dependent on wind energy.

This modeling exercise was performed for demonstrational purposes. The selection of different hypothetical disruptions, other analysis periods, or some other assumptions might result in different estimates of resilience indicators and impacts on the energy system.

0.6

0.7

0.8

0.9

1

1.1

1.2

1.3

1.4

1.5

2024

2025

2026

2027

2028

2029

2030

2031

2032

2033

2034

2035

SWI

Year

SC1

SC2

SC1\_D4

SC2\_D4

2500

3000

3500

4000

4500

5000

5500

6000

6500

7000

2024

2025

2026

2027

2028

2029

2030

2031

2032

2033

2034

2035

H

HI

Year

SC1

SC2

SC1\_D4

SC2\_D4

## (a) (b)

**Figure 12.** Diversity indicators in the case of the loss of wind generators: (**a**) SWI; (**b**) HHI.

### 5. Conclusions

In this paper, a framework of quantitative indicators used to assess the resilience of energy systems was proposed. The empirical application of the theoretically derived indicators allowed for demonstrating the performance of the resilience indicators under different shocks in the prospective energy system.

Resilience indicators can be divided into two types depending on what is being measured within the energy system: capacity (attributes-based) or performance in the presence of disruption (performance-based).

Resilience indicators, which measure the capacity of the energy system to absorb the impact of disruptions, are consistent with the attributes of the energy system and its components. These indicators measure what makes the energy system resilient. Typically, these include but are not limited to the number of supply and import sources, generators, spare parts, and transmission lines and pipelines; the capacities and lengths of those lines; centrality and modularity in the energy system; the availability of distributed energy and microgrids; diversity (shares, SWI, HHI); the largest single source; energy import dependence; the RES share, spare capacity, and energy reserves; cost stability; and level of energy demand. Some of these indicators (e.g., import dependence, RES share, diversity) also might be employed to measure the changes in an energy system during the disruption.

Resilience indicators, which measure the performance of the energy system in the presence of disruptions, allow for measuring changes in an energy system’s resilience. These indicators demonstrate how resilient the energy system is in the case of disruption. They are not directly based on system characteristics but instead measure how well the energy system performs in the presence of disruption. The main resilience indicators of this type are energy not supplied, time of unserved energy, and cost change. Performance-based indicators can be used to measure the resilience of energy systems in different types of disruptions that cause the loss of energy system elements. The type of disruption depends on which elements or components (e.g., lines, generators, fuel supply) in the energy system are lost.

The demonstrational calculations revealed that one of the most important factors that impact energy system resilience is the electricity production mix in the prospective energy system. Diversification plays a considerable role in absorbing the impacts of the disruption. Diversity is also one of the key features for the ability to restabilize an energy system. In the case of disruptions, it allows an easier shift from one technology to another, typically with the lowest costs, if available at the disruption moment. Lower dependence on energy imports and a higher share of RES in electricity production results in higher energy system resilience.

The proposed indicator framework allows for assessing energy system resilience at the present moment and for the future. Estimates of the resilience indicators measure an energy system’s resilience to separate disruptions or combinations of disruptions at different times in the future. The proposed resilience indicators that capture certain aspects of resilience of energy systems can be used in the planning and design of energy systems. This will also allow for comparing different development scenarios of the energy system that may reflect different system development strategies.

The framework for assessing the resilience of the energy system presented in this paper is based on a quantitative assessment approach. However, energy system resilience as a topic requires a holistic evaluation approach. In order to obtain a complete picture, possible future research might include a qualitative assessment approach to the proposed framework.

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### References

1. European Commission (Directorate-General for Energy). *Clean Energy for All Europeans*; European Commission (DirectorateGeneral for Energy): Brussels, Belgium, 2019; ISBN 9789279998430.
2. European Commission. Energy and the Green Deal. Available online: [https://ec.europa.eu/info/strategy/priorities-2019-2024/ european-green-deal/energy-and-green-deal\_en](https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/energy-and-green-deal_en) (accessed on 17 May 2022).
3. International Energy Agency (IEA). *Making the Energy Sector More Resilient to Climate Change*; International Energy Agency: Paris, France, 2015; p. 16.
4. Chaudry, M.; Ekins, P.; Ramachandran, K.; Shakoor, A.; Skea, J.; Strbac, G.; Wang, X.; Whitaker, J. *Building a Resilient UK Energy System: Working Paper*; The UK Energy Research Centre: London, UK, 2009.
5. Jewell, J. *The IEA Model of Short-Term Energy Security (MOSES)—Primary Energy Sources and Secondary Fuels*; International Energy Agency: Paris, France, 2011.
6. Espinoza, S.; Panteli, M.; Mancarella, P.; Rudnick, H. Multi-phase assessment and adaptation of power systems resilience to natural hazards. *Electr. Power Syst. Res.* **2016**, *136*, 352–361. [[CrossRef]](http://doi.org/10.1016/j.epsr.2016.03.019)
7. Ciapessoni, E.; Cirio, D.; Pitto, A.; Panteli, M.; Van Harte, M.; Mak, C. Defining Power System Resilience. *Electra* **2019**, *306*, 32–34. 8. Molyneaux, L.; Brown, C.; Wagner, L.; Foster, J. Measuring resilience in energy systems: Insights from a range of disciplines. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1068–1079. [[CrossRef]](http://doi.org/10.1016/j.rser.2016.01.063)
8. Gholami, A.; Shekari, T.; Amirioun, M.H.; Aminifar, F.; Amini, M.H.; Sargolzaei, A. Toward a consensus on the definition and taxonomy of power system resilience. *IEEE Access* **2018**, *6*, 32035–32053. [[CrossRef]](http://doi.org/10.1109/ACCESS.2018.2845378)
9. Arghandeh, R.; Von Meier, A.; Mehrmanesh, L.; Mili, L. On the definition of cyber-physical resilience in power systems. *Renew. Sustain. Energy Rev.* **2016**, *58*, 1060–1069. [[CrossRef]](http://doi.org/10.1016/j.rser.2015.12.193)
10. Azzuni, A.; Breyer, C. Definitions and dimensions of energy security: A literature review. *Wiley Interdiscip. Rev. Energy Environ.* **2018**, *7*, e268. [[CrossRef]](http://doi.org/10.1002/wene.268)
11. Jewell, J.; Cherp, A.; Riahi, K. Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices. *Energy Policy* **2014**, *65*, 743–760. [[CrossRef]](http://doi.org/10.1016/j.enpol.2013.10.051)
12. Sovacool, B.K. Evaluating energy security in the Asia pacific: Towards a more comprehensive approach. *Energy Policy* **2011**, *39*, 7472–7479. [[CrossRef]](http://doi.org/10.1016/j.enpol.2010.10.008)
13. Cherp, A.; Jewell, J. The concept of energy security: Beyond the four as. *Energy Policy* **2014**, *75*, 415–421. [[CrossRef]](http://doi.org/10.1016/j.enpol.2014.09.005)
14. Gracceva, F.; Zeniewski, P. A systemic approach to assessing energy security in a low-carbon EU energy system. *Appl. Energy* **2014**, *123*, 335–348. [[CrossRef]](http://doi.org/10.1016/j.apenergy.2013.12.018)
15. Hosseini, S.; Barker, K. A Bayesian network model for resilience-based supplier selection. *Int. J. Prod. Econ.* **2016**, *180*, 68–87. [[CrossRef]](http://doi.org/10.1016/j.ijpe.2016.07.007)
16. Shen, L.; Cassottana, B.; Tang, L.C. Statistical trend tests for resilience of power systems. *Reliab. Eng. Syst. Saf.* **2018**, *177*, 138–147. [[CrossRef]](http://doi.org/10.1016/j.ress.2018.05.006)
17. Panteli, M.; Mancarella, P. Modeling and evaluating the resilience of critical electrical power infrastructure to extreme weather events. *IEEE Syst. J.* **2017**, *11*, 1733–1742. [[CrossRef]](http://doi.org/10.1109/JSYST.2015.2389272)
18. Fang, Y.P.; Sansavini, G. Optimum post-disruption restoration under uncertainty for enhancing critical infrastructure resilience. *Reliab. Eng. Syst. Saf.* **2019**, *185*, 1–11. [[CrossRef]](http://doi.org/10.1016/j.ress.2018.12.002)
19. Senkel, A.; Bode, C.; Schmitz, G. Quantification of the resilience of integrated energy systems using dynamic simulation. *Reliab. Eng. Syst. Saf.* **2021**, *209*, 107447. [[CrossRef]](http://doi.org/10.1016/j.ress.2021.107447)
20. Ahmadi, S.; Khorasani, A.H.F.; Vakili, A.; Saboohi, Y.; Tsatsaronis, G. Developing an innovating optimization framework for enhancing the long-term energy system resilience against climate change disruptive events. *Energy Strateg. Rev.* **2022**, *40*, 100820. [[CrossRef]](http://doi.org/10.1016/j.esr.2022.100820)
21. Chen, B.; Chen, C.; Wang, J.; Butler-Purry, K.L. Sequential Service Restoration for Unbalanced Distribution Systems and Microgrids. *IEEE Trans. Smart Grid* **2018**, *9*, 6793–6805. [[CrossRef]](http://doi.org/10.1109/TSG.2017.2723798)
22. Yuan, W.; Wang, J.; Qiu, F.; Chen, C.; Kang, C.; Zeng, B. Robust Optimization-Based Resilient Distribution Network Planning Against Natural Disasters. *IEEE Trans. Smart Grid* **2016**, *7*, 2817–2826. [[CrossRef]](http://doi.org/10.1109/TSG.2015.2513048)
23. Nezamoddini, N.; Mousavian, S.; Erol-Kantarci, M. A risk optimization model for enhanced power grid resilience against physical attacks. *Electr. Power Syst. Res.* **2017**, *143*, 329–338. [[CrossRef]](http://doi.org/10.1016/j.epsr.2016.08.046)
24. Fotouhi, H.; Moryadee, S.; Miller-Hooks, E. Quantifying the resilience of an urban traffic-electric power coupled system. *Reliab. Eng. Syst. Saf.* **2017**, *163*, 79–94. [[CrossRef]](http://doi.org/10.1016/j.ress.2017.01.026)
25. Almoghathawi, Y.; Barker, K.; Albert, L.A. Resilience-driven restoration model for interdependent infrastructure networks. *Reliab. Eng. Syst. Saf.* **2019**, *185*, 12–23. [[CrossRef]](http://doi.org/10.1016/j.ress.2018.12.006)
26. Uemichi, A.; Yagi, M.; Oikawa, R.; Yamasaki, Y.; Kaneko, S. Multi-objective optimization to determine installation capacity of distributed power generation equipment considering energy-resilience against disasters. *Energy Procedia* **2019**, *158*, 6538–6543. [[CrossRef]](http://doi.org/10.1016/j.egypro.2019.01.104)
27. Javadi, E.A.; Joorabian, M.; Barati, H. A sustainable framework for resilience enhancement of integrated energy systems in the presence of energy storage systems and fast-acting flexible loads. *J. Energy Storage* **2022**, *49*, 104099. [[CrossRef]](http://doi.org/10.1016/j.est.2022.104099)
28. Li, X.; Du, X.; Jiang, T.; Zhang, R.; Chen, H. Coordinating multi-energy to improve urban integrated energy system resilience against extreme weather events. *Appl. Energy* **2022**, *309*, 118455. [[CrossRef]](http://doi.org/10.1016/j.apenergy.2021.118455)
29. Sun, Q.; Wu, Z.; Ma, Z.; Gu, W.; Zhang, X.P.; Lu, Y.; Liu, P. Resilience enhancement strategy for multi-energy systems considering multi-stage recovery process and multi-energy coordination. *Energy* **2022**, *241*, 122834. [[CrossRef]](http://doi.org/10.1016/j.energy.2021.122834)
30. Hoettecke, L.; Thiem, S.; Schäfer, J.; Niessen, S. Resilience optimization of multi-modal energy supply systems: Case study in German metal industry. *Comput. Chem. Eng.* **2022**, *162*, 107824. [[CrossRef]](http://doi.org/10.1016/j.compchemeng.2022.107824)
31. Thompson, J.R.; Frezza, D.; Necioglu, B.; Cohen, M.L.; Hoffman, K.; Rosfjord, K. Interdependent Critical Infrastructure Model (ICIM): An agent-based model of power and water infrastructure. *Int. J. Crit. Infrastruct. Prot.* **2019**, *24*, 144–165. [[CrossRef]](http://doi.org/10.1016/j.ijcip.2018.12.002)
32. Dehghanpour, K.; Colson, C.; Nehrir, H. A survey on smart agent-based microgrids for resilient/self-healing grids. *Energies* **2017**, *10*, 620. [[CrossRef]](http://doi.org/10.3390/en10050620)
33. Ren, F.; Zhang, M.; Soetanto, D.; Su, X. Conceptual design of a multi-agent system for interconnected power systems restoration. *IEEE Trans. Power Syst.* **2012**, *27*, 732–740. [[CrossRef]](http://doi.org/10.1109/TPWRS.2011.2177866)
34. Nan, C.; Sansavini, G. A quantitative method for assessing resilience of interdependent infrastructures. *Reliab. Eng. Syst. Saf.* **2017**, *157*, 35–53. [[CrossRef]](http://doi.org/10.1016/j.ress.2016.08.013)
35. Panteli, M.; Mancarella, P.; Trakas, D.N.; Kyriakides, E.; Hatziargyriou, N.D. Metrics and Quantification of Operational and Infrastructure Resilience in Power Systems. *IEEE Trans. Power Syst.* **2017**, *32*, 4732–4742. [[CrossRef]](http://doi.org/10.1109/TPWRS.2017.2664141)
36. Jufri, F.H.; Widiputra, V.; Jung, J. State-of-the-art review on power grid resilience to extreme weather events: Definitions, frameworks, quantitative assessment methodologies, and enhancement strategies. *Appl. Energy* **2019**, *239*, 1049–1065. [[CrossRef]](http://doi.org/10.1016/j.apenergy.2019.02.017)
37. Roege, P.E.; Collier, Z.A.; Mancillas, J.; McDonagh, J.A.; Linkov, I. Metrics for energy resilience. *Energy Policy* **2014**, *72*, 249–256. [[CrossRef]](http://doi.org/10.1016/j.enpol.2014.04.012)
38. Mujjuni, F.; Betts, T.; To, L.S.; Blanchard, R.E. Resilience a means to development: A resilience assessment framework and a catalogue of indicators. *Renew. Sustain. Energy Rev.* **2021**, *152*, 111684. [[CrossRef]](http://doi.org/10.1016/j.rser.2021.111684)
39. Raoufi, H.; Vahidinasab, V.; Mehran, K. Power systems resilience metrics: A comprehensive review of challenges and outlook. *Sustainability* **2020**, *12*, 9698. [[CrossRef]](http://doi.org/10.3390/su12229698)
40. Watson, J.-P.; Guttromson, R.; Silva-Monroy, C.; Jeffers, R.; Jones, K.; Ellison, J.; Rath, C.; Gearhart, J.; Jones, D.; Corbet, T.; et al. *Conceptual Framework for Developing Resilience Metrics for the Electricity, Oil, and Gas Sectors in the United States*; Office of Electricity: Washington, DC, USA, 2015.
41. Vugrin, E.; Castillo, A.; Silva-Monroy, C. *Resilience Metrics for the Electric Power System: A Performance-Based Approach*; Sandia National Laboratories: Albuquerque, NM, USA, 2017.
42. Binder, C.R.; Mühlemeier, S.; Wyss, R. An indicator-based approach for analyzing the resilience of transitions for energy regions. Part I: Theoretical and conceptual considerations. *Energies* **2017**, *10*, 36. [[CrossRef]](http://doi.org/10.3390/en10010036)
43. Gasser, P.; Cinelli, M.; Labijak, A.; Spada, M.; Burgherr, P.; Kadzin´ski, M.; Stojadinovic´, B. Quantifying electricity supply resilience of countries with robust efficiency analysis. *Energies* **2020**, *13*, 1535. [[CrossRef]](http://doi.org/10.3390/en13071535)
44. Zhang, Y.; Liu, W.; Shi, Q.; Huang, Y.; Huang, S. Resilience assessment of multi-decision complex energy interconnection system. *Int. J. Electr. Power Energy Syst.* **2022**, *137*, 107809. [[CrossRef]](http://doi.org/10.1016/j.ijepes.2021.107809)
45. Zhao, Q.; Du, Y.; Zhang, T.; Zhang, W. Resilience index system and comprehensive assessment method for distribution network considering multi-energy coordination. *Int. J. Electr. Power Energy Syst.* **2021**, *133*, 107211. [[CrossRef]](http://doi.org/10.1016/j.ijepes.2021.107211)
46. Karagiannis, M.G.; Chondrogiannis, S.; Krausmann, E.; Turksezer, Z. Power grid recovery after natural hazard impact. *Jt. Res. Cent. Eur. Union* **2017**. [[CrossRef]](http://doi.org/10.2760/87402)
47. Kruyt, B.; van Vuuren, D.P.; de Vries, H.J.M.; Groenenberg, H. Indicators for energy security. *Energy Policy* **2009**, *37*, 2166–2181. [[CrossRef]](http://doi.org/10.1016/j.enpol.2009.02.006)
48. Stirling, A. Diversity and ignorance in electricity supply investment. Addressing the solution rather than the problem. *Energy Policy* **1994**, *22*, 195–216. [[CrossRef]](http://doi.org/10.1016/0301-4215(94)90159-7)
49. Fedor, P.J.; Spellerberg, I.F. Shannon–Wiener Index. In *Reference Module in Earth Systems and Environmental Sciences*; Elsevier: Amsterdam, The Netherlands, 2013.
50. Grubb, M.; Butler, L.; Twomey, P. Diversity and security in UK electricity generation: The influence of low-carbon objectives. *Energy Policy* **2006**, *34*, 4050–4062. [[CrossRef]](http://doi.org/10.1016/j.enpol.2005.09.004)
51. Martišauskas, L.; Augutis, J.; Krikštolaitis, R. Methodology for energy security assessment considering energy system resilience to disruptions. *Energy Strateg. Rev.* **2018**, *22*, 106–118. [[CrossRef]](http://doi.org/10.1016/j.esr.2018.08.007)
52. Howells, M.; Rogner, H.; Strachan, N.; Heaps, C.; Huntington, H.; Kypreos, S.; Hughes, A.; Silveira, S.; DeCarolis, J.; Bazillian, M.; et al. OSeMOSYS: The Open Source Energy Modeling System. An introduction to its ethos, structure and development. *Energy Policy* **2011**, *39*, 5850–5870. [[CrossRef]](http://doi.org/10.1016/j.enpol.2011.06.033)
53. OSeMOSYS—Home. Available online: <http://www.osemosys.org/> (accessed on 18 February 2022).
54. REEEM Home|REEEM. Available online: <https://www.reeem.org/> (accessed on 24 February 2022).
55. REEEM-D6.2\_Regional Energy Security Case Study of the Baltic Region and Finland|Zenodo. Available online: [https://zenodo. org/record/3368544#.Yhc2mZaxWUk](https://zenodo.org/record/3368544#.Yhc2mZaxWUk) (accessed on 24 February 2022).
56. Henke, H.T.J.; Gardumi, F.; Howells, M. The open source electricity Model Base for Europe—An engagement framework for open and transparent European energy modelling. *Energy* **2022**, *239*, 121973. [[CrossRef]](http://doi.org/10.1016/j.energy.2021.121973)
57. Times|REEEM. Available online: <https://www.reeem.org/times/> (accessed on 25 February 2022).
58. Lithuanian Electricity Transmission System Operator LITGRID report. In *Development Plan of the Electric Power System and Transmission Grid 2021-2030*; LITGRID: Vilnius, Lithuania, 2021; p. 54. Available online: [https://www.litgrid.eu/index.php/griddevelopment-/-electricity-transmission-grid-ten-year-development-plan/3851](https://www.litgrid.eu/index.php/grid-development-/-electricity-transmission-grid-ten-year-development-plan/3851) (accessed on 25 February 2022).
59. Open Energy Platform. Available online: <https://openenergy-platform.org/dataedit/view/scenario?query=mesca> (accessed on 25 February 2022).
60. REEEM-D1.2a\_First Integrated Impact Report|Zenodo. Available online: <https://zenodo.org/record/3366029#.YhiWiJaxWUk>(accessed on 25 February 2022).
61. 2020 Climate & Energy Package. Available online: [https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2020 -climate-energy-package\_en](https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2020-climate-energy-package_en) (accessed on 25 February 2022).
62. 2030 Climate & ENERGY framework. Available online: [https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2030 -climate-energy-framework\_en](https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2030-climate-energy-framework_en) (accessed on 25 February 2022).
63. Roadmap 2050. Available online: <https://www.roadmap2050.eu/> (accessed on 25 February 2022).
64. The Paris Agreement|UNFCCC. Available online: [https://unfccc.int/process-and-meetings/the-paris-agreement/the-parisagreement](https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement) (accessed on 25 February 2022).
65. Ministry of Energy of the Republic of Lithuania. *National Energy Independence Strategy of the Republic of Lithuania*; Ministry of Energy of the Republic of Lithuania: Vilnius, Lithuania, 2018.