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Design and Establishment of Ontology for Sustainable Bioenergy †

Adelina Ivanova [1,*], Boryana Deliyska [1] and Anna Rozeva [2]

[1] Faculty of Forest Industry, University of Forestry, 1756 Sofia, Bulgaria; deliyska@ltu.bg
[2] Faculty of Applied Mathematics and Informatics, Technical University of Sofia, 1000 Sofia, Bulgaria; arozeva@tu-sofia.bg
* Correspondence: aivanova@ltu.bg
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Abstract

Bioenergy (including biofuel) production and use are prerequisites for reducing greenhouse emissions and achieving sustainable development. In this work, on the basis of review and analysis of research achievements and elaborated ontologies in the field, an ontology of sustainable bioenergy is proposed. A methodology for its development includes: goals and scope definition, text corpus composition and extraction of the main concepts, controlled vocabulary and thesaurus building, ontology coding, reasoning, verification and querying. The established ontology has links to other related ontologies and is published in GitHub/Borydel/OSBE repository. Further extension of the sustainable bioenergy ontology is planned as well as its embedding in a dedicated repository.

Keywords: ontology modeling; methodology for ontology design; sustainable development; bioenergy

1. Introduction

1.1. Importance of Renewable Energy Sources

Renewable energy sources (RESs) have become an important factor in tackling climate change because of their sustainability and contribution to reducing greenhouse gas emissions. Traditional energy production is known to generate more than 74% of total greenhouse gas (GHG) emissions. Renewable energy production (wind, solar, seawater, freshwater, geothermal and biomass) therefore plays an important role in achieving a circular economy, ensuring lower energy dependence and prices. Circular economy is a model of production and consumption that minimizes waste by involving it in subsequent production or consumption.

In the European Union (EU), the share of RESs in energy consumption for 2020 is on average 21.2%, and in Bulgaria—23.3% [1]. According to Directive 2018/2001 [2], by 2030 at least 27% of the energy in EU must be produced from RESs. In recent years, a number of natural, social and political events have led to reducing yield and consumption of solid fossil fuels, oil and natural gas, as well as wind and solar RESs. According to the Energy Roadmap [3], by 2050 the EU is committed to reducing GHG emissions to 80–95% below the 1990 levels, in order to ensure competitiveness and decarbonization of economy and security of the energy supply. Thus, the importance of RESs, including biomass for biofuel and bioenergy production substantially increases and nowadays, biomass becoming

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predominant. This fact follows from Eurostat records for 2015 where the share in RESs was more than 63%, and it is generally growing by an average of 3% by 2022 [4]. The International Energy Agency (IEA), as well as the International Renewable Energy Agency (IRENA), point out that the advanced bioenergy is an essential component of a future global low-carbon energy system. Moreover, the energy sector currently produces more than 75% of GHG emissions globally [5].

Achieving environmentally friendly bioenergy production and consumption depends on the formulation of long-term sustainability strategy, including study of biological resources, market, investments required, risks, etc.

1.2. Criteria and Indicators for Sustainable Production and Use of Bioenergy

Among the well-known Sustainable Development Goal (SDG) indicators [6], biomass, biofuel and bioenergy are not specifically mentioned, but they have the potential to impact all 17 goals, especially SDG 7, 3 and 13. Thus, Global Bioenergy Partnership [7] offers 24 bioenergy sustainability indicators that correspond to the three pillars of sustainable development—ecological, social and economic. The ISO 13065 standard [8], edited in 2021, regulates the sustainable bioenergy criteria. The theme of sustainable technologies for the conversion of biomass into biofuels and bioenergy is widely represented in numerous studies and projects. The strategies of IEA for ETP (Energy Technology Perspectives) 2 °C Scenario (2DS) and ETP Beyond 2 °C Scenario (B2DS) are developed and recognized [9]. Directive 2018/2001 [2] contains bioenergy sustainability criteria and GHG emission reduction criteria for biofuels. It establishes permissible values of the intensity of GHG emissions in the collection and transportation of biomass, the production of biofuels and the final consumption of bioenergy.

All these studies and documents are based on mathematical, economic and financial models. Some ontologies as means of systematization and structuring shareable and reusable knowledge in the area have been developed as well.

1.3. Analysis of Ontologies for Bioenergy, Biofuels and Biomass

In general, ontologies are implemented as a universal tool for creating information models in all fields of knowledge. The accumulated knowledge in the area of bioenergy has been synthesized into a number of domain and application ontologies. The most representative of these are:

- BiOnto—for a sustainable bioeconomy and organic products; it contains biomass types and biorefining technologies [10].
- Bioenergy ontology—for biomass types, processing technologies and products [11].
- SCB—an ontology for the use of sugarcane waste for bioenergy production [12].
- MENGO (extension of Gene Ontology (GO))—contains 660 terms on microbial metabolisms in biofuel production [13].
- Biomass—one of the ontologies of the project AURORAL (Architecture for Unified Regional and Open digital ecosystems for Smart Communities and Rural Areas Large scale application) for digitization of the development in seven European rural regions [14].
- Biomass and biofuels ontology—for biomass and extracted solid fuels [15].
- BIOREFINERY—an ontology for the characteristics of biomass types and transformation processes into biofuels [16], etc.

Most of these ontologies have been created with well-known ontology languages, RDF (Resource Description Framework) and OWL (Web Ontology Language), according to the W3C [17] standard, but are not reusable due to the lack of dedicated ontology repositories for publication, mapping, merging, linking to other ontologies and other user services.

No ontology for sustainable bioenergy was found, which is the goal of the present work. Regardless of the limited possibilities for connection with the above-mentioned ontologies, such an ontology will complement and expand knowledge and can become a basis (metadata) for the development of information systems in the field. The ontology being proposed here considers the requirements for sustainable bioenergy (SBE), namely:

- The source (biomass) is sustainably harvested from farmland, forest or from waste/residues;
- The biomass is sustainably converted into energy products (biofuels, heat, electricity, etc.);
- It replaces GHG-intensive fuels.

Furthermore, it is also based on the authors' previous research and work on ontologies in the field of sustainable development [18,19].

The rest of our work is organized as follows: The following section presents a methodology for building an ontology of sustainable bioenergy (OSBE). Section 3 discusses the obtained results, their publication and dissemination. The conclusion is a summary of the achievements and presents directions for future research and development for the definition and analysis of sustainability in specific biofuel and bioenergy industries.

2. Methodology for Designing an Ontology for Sustainable Bioenergy

The methodology for an ontology design process includes the following stages: (1) ontology goal and range definition; (2) SBE text corpus composition; (3) text mining and SBE concept extraction; (4) SBE-controlled vocabulary and thesaurus compilation; (5) OSBE formalization (coding); (6) OSBE evaluation through reasoning, consistency verification and querying.

2.1. OSBE Goal and Range Definition

Having specified our motivation, the main goal of OSBE is to classify and structure shareable and reusable knowledge about sustainability of bioenergy as well as to provide tools to help users extract the necessary domain knowledge for decision-making activities. OSBE comprises requirements, methods, strategies, algorithms, techniques, software tools, and respective resources in the area.

Other goals of OSBE are to:

- Establish links with current ontologies for RESs, sustainable development, systems and processes that have common terms with OSBE;
- Provide open access to OSBE code.

The range of OSBE is determined using existing ontologies for bioenergy, bioresources and biofuels, as well as the one for sustainable development (Figure 1):

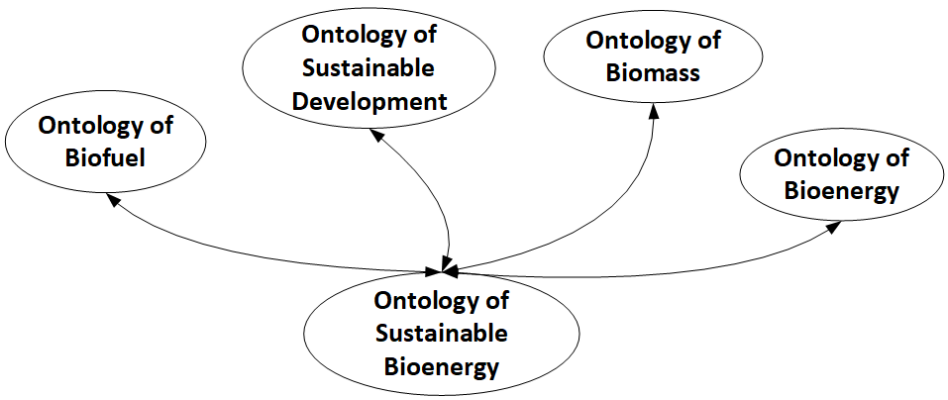

Figure 1. OSBE links to other ontologies (own source).

2.2. OSBE Text Corpus Composition

The text corpus for the analysis and extraction of relevant terms is composed from the document files of [1,2,4,7,8,20–22] in the research area. For the time of the present study, this text corpus has been periodically updated given the dynamics in sustainable bioenergy research and publication activities.

2.3. Text Mining and OSBE Concept Extraction

Text mining of the above text corpus (for the essential term elicitation) has been implemented manually As a result the following main concepts have been established:

Sustainable bioenergy—bioenergy that meets the following criteria: technological soundness and accessibility of technology; cost-effectiveness, sound cost–benefit ratios, coherence with local and national development priorities, and ecological soundness [22].

Sustainable biomass—organic waste and residue, produced with GHG savings, preserving forests, soil, water and biodiversity, and providing for biofuel production in accordance with renewable requirements. The criteria for sustainable biomass vary for different types of biomass—forest, agricultural, domestic, and industrial.

Sustainable biofuel (solid, liquid, gas) is a biofuel produced from sustainable biomass by using technology that does not violate emission reduction criteria. A distinction is made between sustainable biofuels for transport, electricity generation and heating/cooling.

Related to the main concepts are the ones derived from Directive (EU) 2018/2001 and Directive (EU) 2023/2413 (known as RED II and RED III) which refer to sustainability criteria and indicators for bioenergy, biofuels and biomass differentiated by environmental, economic and social aspects [2,21]. Standards for the production of solid, liquid and gas biofuels and associated certificates have been established. For example, known certificates for sustainable biomass include: SBP (Sustainable Biomass Program) [23]; ISCC—based on the European Directive RED II [24]; ISCC Plus—an extension of ISCC [25]; GGL [26]; 2BS [27] (Biomass and Biofuel Sustainability); ENplus—for the quality of wood pellets for domestic boilers and stoves [28]; INS (Italian National Scheme)—for biofuels and bioliquid sustainability [29]; FSC (Forest Biomass Certificate) [30]; PEFC (Programme for the Endorsement of Forest Certification) [31], etc. These certificates have links to the so-called voluntary scheme, a sustainability certification system designed to demonstrate compliance with biofuel sustainability criteria. According to GBEP [7] 24 sustainability indicators for bioenergy exist, such as quantitative or qualitative minimum number of parameters for measuring the achievement of the sustainability criterion. There are links between them and the indicators of SDG targets [32], which are themselves considered a suitable normative framework for the sustainable bioeconomy [33]. SBE is differentiated into environmental, economic and social. The environmental one involves air, water, soil quality, including GHG emission and other air pollutants, land and forest use, and biodiversity safety. Economic SBE indicators concern energy use, balance, distribution and diversity, productivity, gross value added etc. Specific social SBE indicators are: impact of biomass feedstock cultivation, allocation and tenure of land for new bioenergy production, steady jobs in the bioenergy sector, etc.

Other subordinate concepts, their instances, links and properties are established and ordered in a list for the subsequent building of a controlled vocabulary and thesaurus. Following the established OSBE range, external concepts related to sustainable bioenergy concepts are retrieved, thus providing for the composition of an additional concept list. Some of these concepts are: landscape, biomass supply, bioelectricity, biogas, pellet, energy consumption, RESs and others related to ontologies pointed out in Figure 1.

2.4. Controlled Vocabulary and Thesaurus Compilation

The related terms extracted from a SBE text corpus are arranged in a common controlled vocabulary. The controlled vocabulary is a tool for organizing standardized and/or generally accepted concepts (terms) in a given area. "Each term of such vocabulary is specified by term identifier (TID), syntactic category (part of speech, PoS), hierarchical and/or associative relations with other terms and definition" [19]. According to standard [34], TID can be: top term (TT) in a controlled vocabulary hierarchy; preferred term (PT)—most appropriate term; related term (RT)—term, associatively linked to another term; narrower term (NT)—subordinate to another term in a hierarchy, non-preferred term (NPT)—an alternative version for a term: synonym, alternative spelling, lexical variant, abbreviation, acronym, etc.

The terms of type RT, NT, NPT explain PTs through associative relations (*is-synonym-of/has-synonym, is-kind-of, is-located-in, is-applied-of* and many others) depending on the specifics of the subject area. On the other hand, the addition of hierarchical relations (*is-a/has-a, is-part-of/has-part, is-instance-of/has-instance, is type-of/has-type*) between the PTs and to TT transforms the vocabulary into a thesaurus.

The terms, linked by hierarchical relations, compose the thesaurus taxonomy. As a rule, "each taxonomy has two main parts—classification (also known as subsumption) and mereology. The classification scheme begins with a so-called *type-of node* label and contains PTs of concepts linked with relations *is-a/has-a* (*is-subclass-of/has-subclass*)" [19]. Node labels are not indexed entities in a thesaurus but serve to build the classification hierarchy. An excerpt of the upper levels of OSBE taxonomy is given in Figure 2.

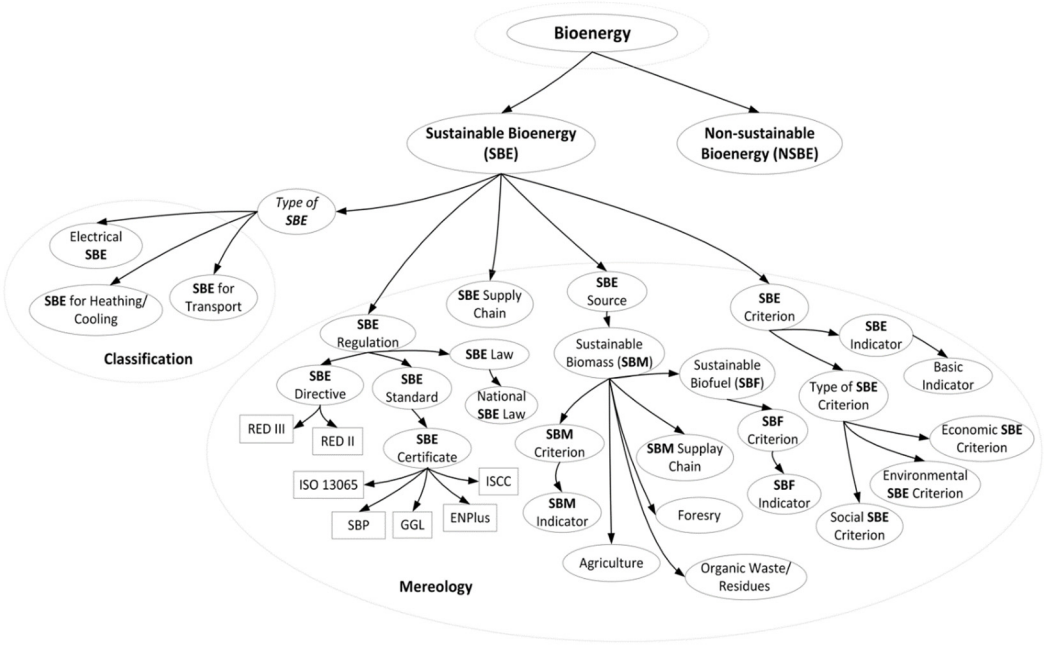

Figure 2. Excerpt of sustainable bioenergy taxonomy (own source).

The following terms are directly subordinate to TT in the mereology part:

SBE Regulation: denotes legal SBE documents—directive, standard and law.

SBE Supply Chain—includes operations regarding production, packaging, transportation, storage and selling the final product to a customer [35].

SBE Source—describes the origin of biomass and wood residue, energy crops, crop residues, organic waste/residues from industry, agriculture, landscape management and households [20]; the biomass is converted to biofuel.

SBE Criterion—a rule or principle for evaluation composed by an indicator. Criterion and indicator can be considered as a platform or framework for measuring the index of SBE. The criterion can be considered within the three pillars of sustainability—environmental, economic and social.

The SBE classification scheme begins with the type of SBE node label. The node label is an ontology element not intended for indexing but for organizing the hierarchy in the ontology classification structure. In this case, the type of SBE denotes the SBE classification and has three main sub-nodes—electrical SBE, SBE for heating and SBE for transport, which refers to ecological and sustainable production of electricity, heating and transport with minimum of GHG emission and dependence on fossil fuels. These three classification principles highlight the main features of SBE management activities. As a principle and for the convenience of future processing, the vocabularies and the thesauri are implemented in databases. Specifically, the OSBE thesaurus is implemented in a local Access database shown on Figure 3.

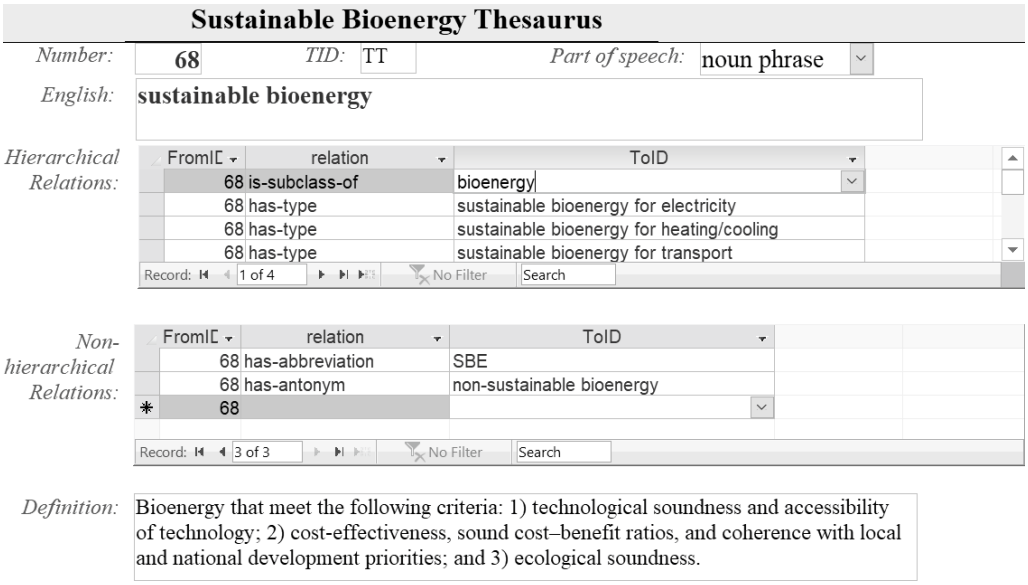

Figure 3. Term in SBE thesaurus database (own source).

"Although a thesaurus has all the components as an ontology, due to its inability for logic-based reasoning it is not reusable in the Semantic Web." [19]. In other words, "an important reason for converting a thesaurus into a formal ontology is the necessity of its machine readability and reuse" [36]. Thus, the MS Access database of the OSBE thesaurus is further on converted to an OWL code by the software application presented in [36]. The thesaurus terms and its relations become OSBE components (classes, instances, properties, etc.).

2.5. Ontology Formalization and Integration with External Ontologies

For the ontology formalization the Semantic Web standard languages RDF and OWL recommended by World Wide Web Consortium (W3C) [37] are used. They are embedded in the open-source Protégé development environment that is available for free and is currently the most used ontology editor [37]. Then, after the thesaurus conversion, OSBE is implemented through the manual introduction of its OWL code file in Protégé 5.6.3 [38]. Furthermore the OSBE content is edited through the addition and update of classes, data properties, object properties, and instances. Currently, OSBE covers 75 classes.

The developed OSBE was connected to some related external ontologies with a free available OWL code, i.e., Common Ontology of Sustainable Development (COSD) [18],

Ontology of Sustainable Development in Economy (OSDE) [39], Ontology of Environmental Sustainable Development (OESD) [40], and Ontology of Social Sustainable Development (OSSD) [41]. External links to these ontologies are manually established in the Ontology Prefixes section of the Protégé main screen through code rows of the following type:

@prefix name = "…" IRI = "ontology IRI"

A sample of the establishment of prefix env for a link to OESD classes is:

@prefix name = "env" IRI = "https://github.com/Borydel/OESD/blob/main/OESD-OWL%20code"

The prefix precedes the entity name in the current ontology, which maps it to one in the external ontology. For example, *env: Waste assimilation* exists in OSBE and OESD too.

After OSBE formalization and external link establishment, it has been investigated through reasoning, verification and querying.

2.6. OSBE Reasoning, Verification and Querying

Ontology reasoning means checking the semantic structure and mutual consistency of the ontological units [19]. Parenthetically, frequent reasoning during ontology building is recommended for the timely discovery of inconsistencies. In Protégé 5.6.3 environment, Pelet, HermiT and other reasoners are embedded [37]. They can also examine the hierarchy correctness. Reasoning is part of the ontology verification.

After reasoning and verification, ontology can be tested for the extraction of knowledge by implementing ontology query languages. The native formal languages embedded in Protégé for knowledge representation and querying are: SPARQL—query language for RDF ontologies; SQWRL—for OWL ontologies; and OWL DL language—one of Description Logics (DL) languages intended for searching a classified ontology. Figure 4 shows a sample DL query.

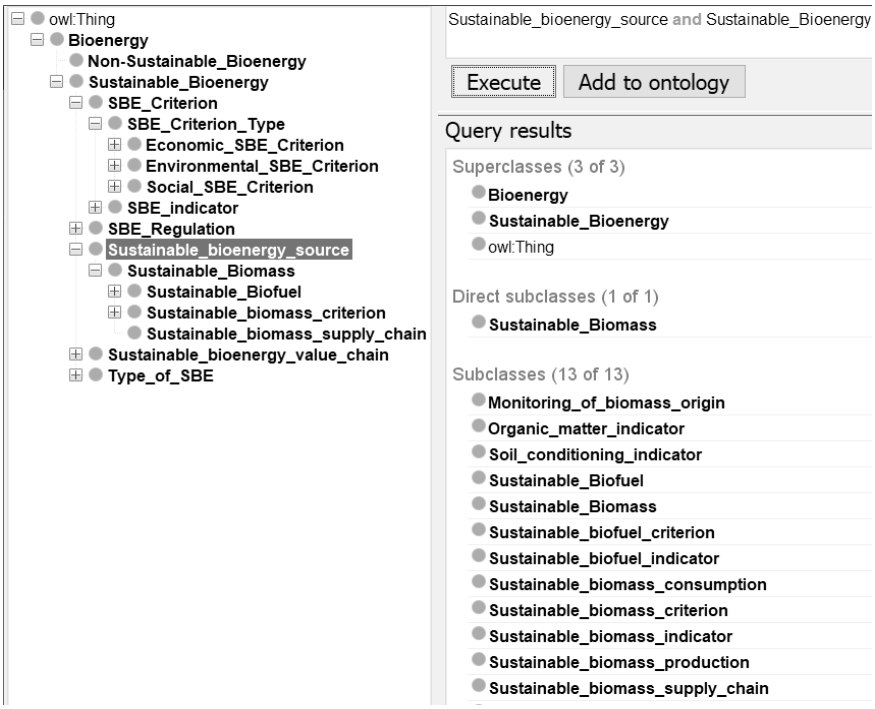

Figure 4. Description Logic query result (own source).

For this purpose, a set of sample queries concerning the ontology class hierarchy are implemented in the respective Protégé tab. The queries can be stored in the ontology repository for future reuse. It should be noted that a key problem in the Semantic Web exists because of the fact that ontology query languages are inappropriate for non-expert users unfamiliar with the semantic technologies. Finding a suitable repository for OSBE publication turns out to be a particular problem.

3. Ontology Publication and Distribution

For an ontology to be usable and shareable on the Web it must be published in an ontology repository. The ontology repositories in the Web space have various navigation, search interfaces and programming languages depending on ontology type. Some of them, except libraries of ontology files, provide services as reasoning, testing, ontology lookup, statistics, mapping and etc. Other ontology repositories, such as Swoogle, Protégé ontology library, Dumontier, etc., are not supported nowadays. Currently, several repositories for OSBE deployment are partly appropriate:

- OntoPortal framework and its instances—BioPortal, AgroPortal, EcoPortal, EarthPortal and other repositories [42].
- AberOWL [43].
- Ontology Lookup Service (OLS)—a repository of biomedical ontologies maintained by the European Bioinformatics Institute (EBI) [44].
- Linked Open Vocabularies (LOV)—curated repository of linked open vocabularies and ontologies [45].
- Ontobee [46].

Dedicated open repositories for sustainable development and particularly for renewable energy were not found.

At present, OSBE description and its OWL code are published in the "Borydel/OSBE" repository on GitHub [47], a versatile multi-purpose hosting platform for software, where they become public and available for further development, and integration into related semantic web applications.

4. Results and Discussion

On the basis of exhaustive review and analysis of research achievements and elaborated ontologies in the field, an ontology of sustainable bioenergy called OSBE covering concepts, regulations, standards, criteria and referring indicators is proposed. OSBE is implemented in OWL for Protégé 5.6.3 environment and at this stage contains 75 classes. Links to related external ontologies in the area of sustainable development are established. OSBE was reasoned, verified and searched by sample queries.

Further work is planned for the OSBE extension, support and embedding in a dedicated repository. It should be noted that for an effective use of different ontology services, an ontology repository integrating OSBE and the related ontologies is required. Later on, this repository can be linked to an appropriate ontology network for the establishment of other inter-domain connections.

5. Conclusions

Bioenergy and biofuel production and use are some of the factors for reducing GHG emissions and achieving sustainable development. The design and implementation of OSBE and its publishing on the Web will increase the available knowledge on bioenergy and will support linkage to other sustainability-related ontologies. The presented methodology for ontology modeling in the field of sustainable use of renewable energy, in particular bioenergy facilitates a more complex multilayered study and analysis of the efficiency and

cost-effectiveness of this subject area. OSBE can serve as a basis for the design and information modeling of the sustainable use of RES. It could help the investigation and assessment of current state, trends and achievements in the development of specific activities in the examined area by enhancing the possibilities for analysis, providing relevant, accurate and timely information.

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Data Availability Statement: OSBE description and its OWL code are published in a dedicated, versatile, multi-purpose GitHub repository [47].

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

COSD	Common Ontology of Sustainable Development
DL	Description Logics
EBI	European Bioinformatics Institute
ETP	Energy Technology Perspectives
EU	European Union
FSC	Forest Biomass Certificate
GBEP	Global Bioenergy Partnership
GHG	Greenhouse Gas
IEA	International Energy Agency
INS	Italian National Scheme
IRENA	International Renewable Energy Agency
ISCC	International Sustainability & Carbon Certification
ISO	International Organization for Standardization
LOV	Linked Open Vocabularies
NER	Named Entity Recognition
NLP	Natural Language Processing
NPT	Non-Preferred Term
NT	Narrower Term
OESD	Ontology of Environmental Sustainable Development
OLS	Ontology Lookup Service
OSBE	Ontology of Sustainable Bioenergy
OSDE	Ontology of Sustainable Development in Economy
OSSD	Ontology of Social Sustainable Development
OWL	Web Ontology Language
PEFC	Programme for the Endorsement of Forest Certification
PT	Preferred Term
RDF	Resource Description Framework
RED	Renewable Energy Directive
RES	Renewable energy sources

RT	Related Term
SBE	Sustainable Bioenergy
SBP	Sustainable Biomass Program
SCB	Sugarcane Bagasse
SDG	Sustainable Development Goal
SPARQL	S+Protocol and RDF Query Language
SQWRL	Semantic Query-Enhanced Web Rule Language
TID	Term Identifier
TT	Top Term
W3C	World Wide Web Consortium

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