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The concept of an ecosystem model to support the transformation to sustainable energy systems

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HIGHLIGHTS

- Ecosystem model development for optimisation of energy systems.
- Combination of analysis, optimisation and simulation modules.
- Integration of the bio-inspired optimisation algorithm.
- Objective is to establish the natural energy systems.

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ABSTRACT

Sustainable development requires measures to decrease energy consumption and to avoid any harmful impact on the environment. In recent years, a lot of research has been focused on designing energy systems by emulating the natural ones. This can be regarded as a novel way to support the transformation to sustainable energy systems. The initial step in forming energy systems of thus type, by emulating the ecosystem approach, is the development of a model for rendering the current situation. To contribute to the solution of this problem, an ecosystem model combining the analysis, optimisation and simulation modules has been developed as part of this study. The commonly used models for energy systems are good predictors of the general energy dynamics and structures. However, they can be inadequate when it comes to describing or predicting the complex phenomena within energy systems, such as the large number of parameters, the many end-users, the potential of the technologies, the assessment of the various environmental impacts and the variety of resources. With the implementation of the ecosystem model there is further expanding of the knowledge of an advanced, self-organising methodology integrated within the model's operation by emulating the natural system dynamics. The ecosystem model could become a valuable tool for developing sustainable energy systems, and allowing the development of the most suitable and sustainable energy system based on the local availability of energy sources.

1. Introduction

The problem with local energy systems is the high consumption of fossil fuels and, consequently, the harmful impact on the environment in the form of climate change due to greenhouse-gas emissions [1]. However, communities could set ambitious objectives by implementing entirely renewable and self-sufficient energy systems [2]. This is particularly relevant for rural municipalities with substantial renewable-energy resource potentials in isolated and remote areas. The main idea behind this research is the organisation of energy systems by emulating natural systems. To achieve optimal model performance, the functioning of the natural systems can be replicated to find the optimal solution. This is to be supported by the development of the energy model and following the natural functioning, which would render the most realistic situation and provide an effective simulation

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for future planning. There have been many previous studies presenting models for optimising the energy supply and use. These models can be divided according to geographical coverage, addressing issues at the regional, municipal or city level. The multi-regional input–output (MRIO) model [3] considered embodied energy uses in urban ecosystems and covered entire supply chains on a regional scale. The dynamic inexact stochastic energy systems planning model (DITS-MEM) was developed to manage municipal energy systems and greenhouse-gas emissions under uncertainty [4]. The city energy system was planned using a the model based on the EnergyPRO tool [5]. Various energy-planning models, energy supply and demand models, simulation models and others have been presented. One example is the energy-planning model addressing intermittent RES presented in Poncelet et al. [6]. A model covering the energy supply and demand simultaneously at urban district level [7] has also been published. The emerging issues of the demand models, such as asymmetric price responses, time-varying demand parameters, triangulation analyses to seasonal and climate-change effects, to mention just a few, were analysed [8]. A guided-search approach for calibrating Building Energy Simulation models (BES models) was presented in [9]. A number of models tackle a specific sector. The model addressing the residential sector for the design and control of buildings to achieve a nearly zero energy target was developed and presented in [10]. Another model was developed for the transport sector, analysing the impacts on the power system of future scenarios involving electric vehicles [11]. Estimation and explanation models of sectors' energy-related CO_2 emissions have also been proposed in [12]. Quantitative tools and methods for the industrial energy and material symbiosis among companies in eco-industrial parks (EIPs) were examined [13]. A hierarchy model of EIPs, respecting the unit, process, plant and industrial network level (which has an advantage in comparison to the others) with advanced modelling approaches for describing each level of performance and efficient optimisation methodologies for solving complex EIP problems was developed. The HDMR surrogate models for multi-level modelling and the optimisation of an EIP at the unit level, the process level and the plant level were designed. The networks at the top EIP level were structured with plant surrogate models for the purposes of model simplification [14]. The modelling framework for the carbon metabolism of the EIP was developed [15]. The plan for the ecosystem model's development is to include all the sectors, not just a specific one. There is a possibility to develop a model that successfully addresses energy and environmental issues together, while currently they are mostly presented separately for the environmental field [16] and for the energy field [17]. There are models developed for a specific community [18] or city [19]. In addition, models that provide an in-depth analysis of the state of the environment with a combination of such an analysis model with energy-simulation models and models with an optimisation method are difficult to find [20]. One type of models that provides an in-depth analysis of the present state of the environment, is that of the metabolism models [21]. These models trace the mass and energy flows within a specific geographical area [22]. The objective of the proposed research is to develop an ecosystem model combining the analysis, optimisation and simulation modules. The added value of the newly developed model would be achieved through the model's organization and the used bio-inspired algorithm, both emulating the functioning of the natural system. However, it is not just a question of the formation of decarbonised energy systems with present energy-efficient technologies. The horizon has to be broadened to include newly invented systems with highly effective technologies and minimal needs for energy. With these actions there is an initial attempt to introduce bionics within the field of energy systems and contribute towards designing sustainable energy systems.

2. Proposed solution

The proposed ecosystem model (ESM) [23] comprises the analysis, simulation and optimisation module. The analysis (i.e., metabolism) module serves as the baseline data foundation for further planning. The simulation module generates several future scenarios and the optimisation module base the decision upon the best available option. The ESM consists of specific modules in order to accomplish more effective functioning of the entire local energy system. The objective has been to develop a comprehensive model that can provide the transformation of energy systems to higher sustainability by replicating the systems in nature. In this manner, the structure of the model, by replicating the natural organisation, the depicted optimisation algorithm and the highlighted environmental component, contributes to designing more natural energy systems. Novel research directions are highlighted by the research results within the evolving field of bionics [24]. The anticipated future pathway in the field of energy bionics is in the development of a bionic energy system, where the bio-inspired ESM would serve as the support tool for the planning activities. The field of bio-inspired algorithms mimics the natural organization from organisms, swarm groups and processes in ecosystems. Accordingly, the implementation of the bio-inspired Non-dominated Sorting Genetic Algorithm II (NSGA-II) [25] is used for the optimisation part of the ESM. With this, the energy systems emulating the functioning of natural systems could be established.

3. ESM model

The development approach for the ESM's construction emulates natural systems and adds value to the field of energy bionics [26]. Energy bionics is recognized as an evolving discipline that provides a broader foundation for innovative solutions [27]. The main purpose of the discipline is to emulate nature in order to propose efficient technical solutions [28]. Through the evolution, natural solutions are recognised as being optimal in comparison to others [29]. Energy bionics leads to further advances in the energy sector such as photosynthesis replication in technological solutions, genetic algorithms [30], bio-inspired wind generators and others. The role of the ESM (see Fig. 1) is to enrich the studies in the field of energy bionics and to develop a comprehensive model consisting of analysis, simulation and optimisation parts. There is a special

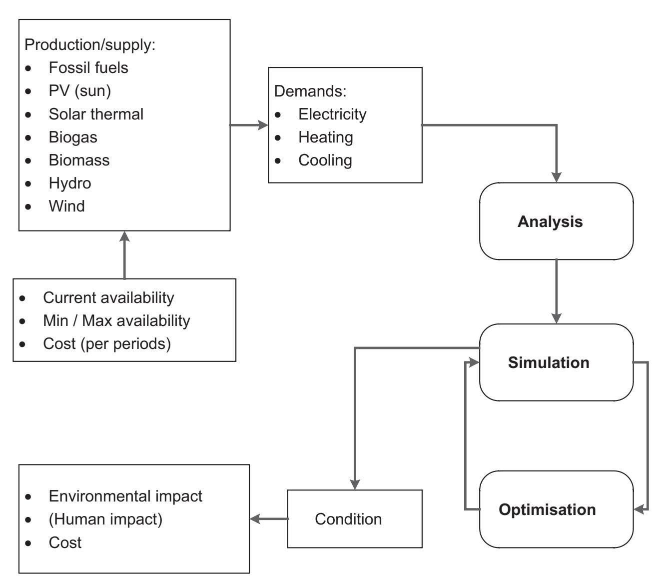

Fig. 1. Overview of the ESM.

emphasis on the environmental part, with calculation of the various emissions due to energy use.

The model is developed from several modules, where each is responsible for a certain activity. The initial step consists of gathering and analysing the data and should be implemented for the purposes of building the metabolism model. In the simulation module the method of generating and estimating the scenarios is implemented. For the development of the optimisation module, the most suitable optimisation algorithm is chosen and adapted to the demands of the specific problem. However, the focus is on the bio-inspired optimisation algorithm and its use within the ESM development. Afterwards, the prototype of the ESM is designed and evaluated.

In the following sub-sections, the three modules (analysis, simulation and optimisation) are presented and discussed.

3.1. Analysis

The analysis module determines the energy model parameters according to the input variables (forest size, annual harvest, ratio of different wood types, quantity of specific farm animals and crops, conversion coefficients, energy supplies, demands, availabilities, cost, etc.) and the relations among them. Such a model consists of equations that define the relations between the different input and output variables, where the determined parameters are the coefficients of the equations. The dependent variables present the observed values, i.e. the cost and environmental influence. Based on data observations over time and the analysis of newer data with different data mining techniques, the mathematical model (i.e., the coefficients of the equations, as well as some additional equation) can be further updated and modified. This on-going activity of tracing the mass and energy flows allows a realization of the self-adapting property of the metabolism model. An overview of the analysis module is presented in Fig. 2. Here the input parameters are: the needs for different supply types (e.g., for which RES there is a need), availabilities of different supplies, the costs of all supplies, the size (i.e., quantity), and type (i.e., electricity and/or thermal energy) of demands.

3.2. Simulation

The simulation is based on a calculation of the mathematical model (equation-based), which is constructed and updated by the analysis module. The simulation module is used to calculate the influence of a particular scenario (i.e., demand size, supply availability, etc.) on the results (i.e., cost, emissions). Fig. 3 presents an overview of the simulation module, where several input parameters are presented. On the demand side the input parameters of the residential demand (electricity demand, thermal demand, dwellings), the industry demand (electricity, thermal demand, workers), the public buildings (electricity demand, thermal demand, volumes), the public lighting (electricity demand, types of lights installed), and the transport (types of cars, types of fuel consumption) are merged into the set of settings, i.e., the quantities that needs to be met by the supply quantities. On the supply side the input parameters are the supply quantities that are to be considered: the production of energy from fossil fuels, from renewable energy source (RES) (PV production, solar thermal production, biogas production, biomass production, hydro production, wind production). The values of these parameters are fed into the mathematical description (equations) of the model that outputs the influence and the costs estimations.

The quantitative simulation includes a calculation of the emissions of all the used resources and the costs of the used resources. The emissions $f_{emissions}$ are calculated as follows

$$f_{emissions} = \sum_{i=1}^{k}\sum_{j=1}^{l} emission_{ij} \tag{1}$$

$$f_{availability} = \sum_{i=1}^{p} availability_i \tag{2}$$

$$f_{availabilityRES} = \sum_{i=1}^{r} availability_i \tag{3}$$

where k is the number of resources (wood biomass, biogas, hydropower, sun, wind, hydrogen, geothermal, natural gas, LPG, oil, coal, nuclear fuel); the first seven (r) types are RES and the next four (p) are non-RES; l is the number of considered emissions (CO_2, SO_2, NOx, CxHy, CO, dust). $emission_{ij}$ is the amount of emissions of type j produced by the resource i.

$$emission_{ij} = weight_j \times availability_i \tag{4}$$

here the factor $weight_j$ is the standard emission factor for the emission j; the amount of resources $availability_i$ is measured in kW h.

The upper and lower limits of each resource type's availability are represented by $Uavailabilty_i$ and $Lavailability_i$; the available

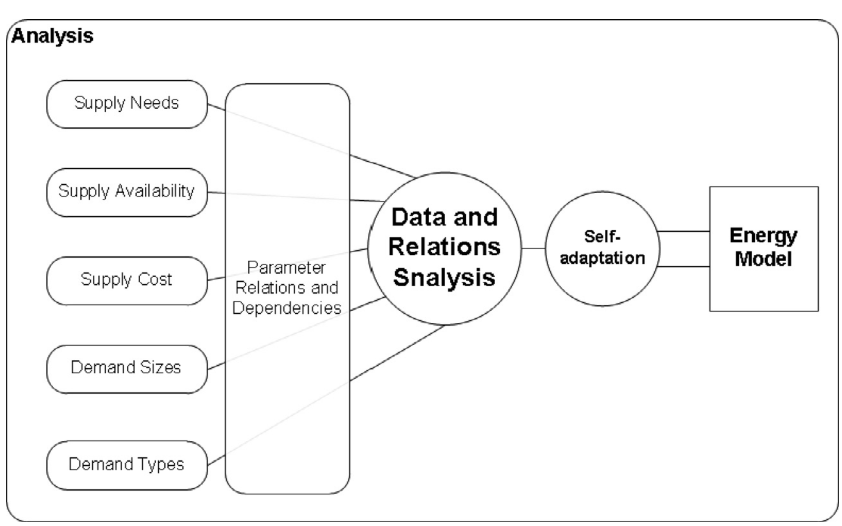

Fig. 2. Overview of the analysis module.

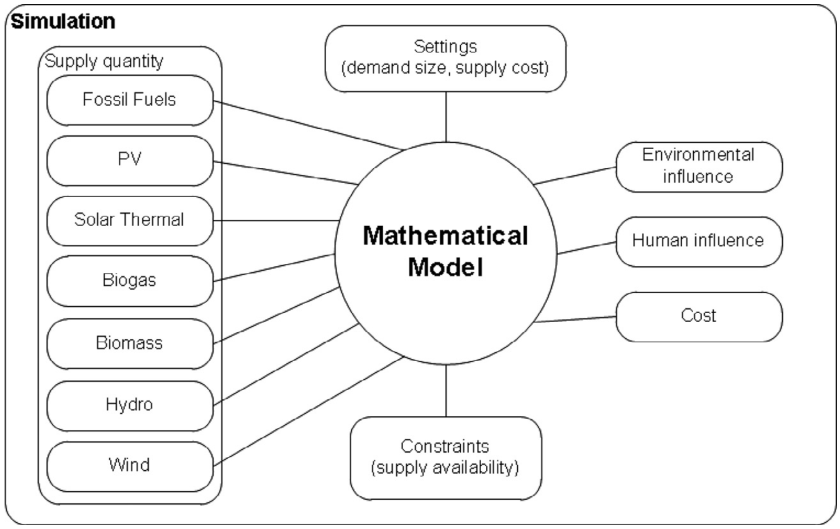

Fig. 3. Overview of the simulation module.

capacity of some resource at a particular time is therefore $Lavailability_i \leqslant availability_i \leqslant Uavailability_i$.

The required capacity of the supplies is equal to the size of the *demand* that is calculated as the sum of the *requests* of all the *s* sectors (households, industry, public sector and public transportation)

$$demand = \sum_{i=1}^{s} request_i \tag{5}$$

To fulfil all the needs the *supply* and *demand* should be equal (the *supply* is the sum of all the required *availabilities* of specific resources)

$$supply = \sum_{i=1}^{k} availability_i \tag{6}$$

To calculate the costs of using all the required resources the following equation is used

$$f_{cost} = \sum_{I=1}^{k} cost_i \tag{7}$$

where $cost_i$ is the cost of using the required bounds of the availability for resource *i*.

$$cost_i = price_i \times availability_i \tag{8}$$

To calculate the bounds of availability for a specific resource, like wood biomass or biogas, additional calculations are required. To determine the capacity of the available wood biomass the forest size, the allowed annual harvest, the ratio of the different wood types and their energy capacity are required. Similarly for the biogas the quantity of specific farm animals and crops, and their energy capacity are required.

The human impact can be calculated as the indirect influence on people's health with respect to the emissions produced in a specific smaller area.

3.3. Optimisation

The overview of the optimisation module is presented in Fig. 4. This module is used together with the simulation module to search for the optimal set of input parameters. This optimal set is defined as the set that allows the wanted output values, which include the availability of resources, the costs, and the quantity of emissions. The search is a fully automatic, numerical optimisation of the input parameters. For each input parameter that is optimised, the limits (the lower and upper bounds) of the parameter should also be defined. The search for viable parameter configurations in terms of the type and capacity of the energy resources for given demand conditions represents a difficult task for energy planners. While RESs are highly desirable their exploitation on a large scale involves other issues, like limited availability, and financial obstacles.

In the case of small sets of input parameters a linear optimisation method can be used, since it allows a quick and efficient calculation of the results. However, when dealing with large areas that have a large number of decision variables (many energy resources and consumers), where many combinations are possible and need to be evaluated, considering multiple, mutually contrasting criteria, an intelligent approach is needed in order to speed-up the search for the optimal set of parameters. Among the intelligent computational approaches, there are several powerful evolutionary-based strategies that can be used for the optimisation of the energy system, like genetic algorithms (GAs) [31], ant-colonies [32], differential evolution [33] and a variety of others. Evolutionary approaches in general have proven search capabilities within different complex problems in engineering systems [34], as well as energy-related problems like photovoltaic [35], wind farm [36], and HVAC systems [37]. Therefore, among the evolutionary-based approaches the GA approach was selected because of its implementation simplicity [38]. The GA belongs to the class of evolutionary algorithms that are search methods that can imitate the principles of the Darwinian theory of evolution. New solutions are generated using techniques inspired by natural evolution, such as selection, crossover, and mutation. To increase the performance of the evolutionary optimisation approach and to obtain a clearer insight into the complex search space with several constraints [39] a multi-objective approach (NSGA-II) is introduced into this module. With this it goes beyond the optimisation tools of some energy models (e.g., HOMER) [40], which are single-objective and tailored for small systems.

The non-dominated Sorting Genetic Algorithm II (NSGA-II) [25] is a non-domination-based genetic algorithm that searches for multi-objective optimisation. During each iteration of the search, the algorithm computes a new generation from the current one using fast-non-dominated-sort, crowding-distance-assignment and applying genetic operators, i.e., crossover, mutation, and selection.

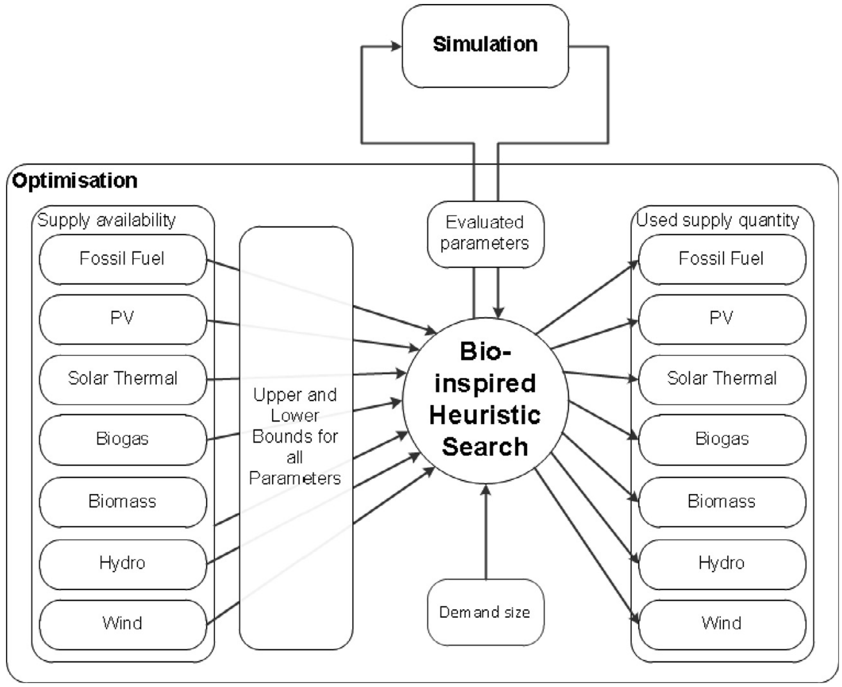

Fig. 4. Overview of the optimisation module.

In the initialization phase a random population of solutions is created. Fast-non-dominated-sort is an efficient approach for partitioning a set of solutions into so-called non-dominated fronts. In order to sort a population according to the level of non-domination, each solution is compared with every other solution in the population. Crowding-distance-assignment is a method for assigning the quality of a solution with the aim that points on the approximation Pareto front should be well-distributed. Crossover and mutation are iteratively applied to the current parent population in order to generate the new offspring population.

The NSGA-II pseudo code is represented in Fig. 5.

The goal is to find the configuration that minimizes the emissions ($f_{emissions}$) and costs (f_{cost}) while minimizing the availability of the non-RES sources ($f_{availability}$) and maximizing the availability of the RES sources ($f_{availabilityRES}$), and still fulfilling all of the energy requests.

```
SetInitialPopulation(P)
Evaluate(P)
FastNondominatedSort(P)
while notEndingCondition(){
     P' = SelectParentsByRank(P)
     Crossover(P', pc)
     Mutation(P', pm)
     U = Marge(P, P')
     F = FastNondominatedSort(U)
     P = 0
     FL = 0
     for each Fi{
            CrowdingDistanceAssignment(Fi)
            if(Size(Fi) + Size(P) > population_size)
                   FL = Fi
            else
                   P = Merge(P, Fi)
     }
     if(Size(P) < population_size)
            FL = SortByRankAndDistance(FL)
            P = FillRemaining(FL)
     Evaluate(P)
}
```

Fig. 5. NSGA-II pseudo code.

$$\min\ F(\bar{x}) = \{f_{emissions},\ f_{cost},\ f_{availability},\ 1/f_{availabilityRES}\} \tag{9}$$

while $\sum_{i=1}^{p} availability_i + \sum_{i=1}^{r} availability_i = demand.$

4. Evaluation

The ESM model was evaluated using the ecosystem model, web-based implementation [23]. The application allows the entry of data about the consumption and production of energy in a municipality; it then charts the data, analyses it and proposes the optimum solution (based on the above objective function) for the consumption of energy in the municipality.

An illustrative example of evaluating the ecosystem model is shown for the Ormož municipality, which is considered to be a small municipality with a reasonable renewable potential to transform its energy system into an entirely renewable one. The Ormož municipality is within the Spodnje Podravje region with a geographical area of 142 km^2 and 12,402 inhabitants.

The current energy consumption for heating purposes in the Ormož municipality has a large share of RESs, especially wood biomass (26.68%), due to the local availability of this specific energy source. The availability of biomass in the Ormož municipality is 25,128 m^3/y. In the current energy balance, 57.7% of the households' heat energy is generated from biomass. To cover these heat requirements, 11,837 m^3/y of biomass is used, representing 28.405 GW h/y of generated energy. The other available biomass resources can be used for heating and power generation as well as for other sectors' requirements in the future. This means 13,291 m^3/y of biomass potential for future exploitation or an extra 31.894 GW h/y of energy potential [41]. There is a plan to install a district heating system based on wood biomass with inclusion of public buildings, service buildings, two industrial companies and residential buildings [42]. Based on this installation, the consumption of wood biomass would increase dramatically. There is also strong interest from biomass providers (forest owners, farmers, wood production companies and others) to establish a municipal supply chain to cover the end-users requirements. Based on these facts, there is a real possibility that the Ormož municipality can be entirely supplied by RESs [41]. In the process of establishing the biomass value chain, the data about harvesting and transportation should also be estimated in order to show the optimal scenario. Establishing the biomass value chain would also contribute towards the energy self-sufficiency of the municipality.

The potential of biogas for the Omrož municipality is estimated to be 6,411,359 m^3/y, from animal waste it is 2,577,192 m^3/y (400,770 m^3/y from pigs, 1,924,572 m^3/y from cattle and 251,850 m^3/y from poultry). The potential energy generated from animal waste is estimated to be 15.463 GW h/y. The potential of biogas from green mass is estimated to be 3,834,167 m^3/y. The evaluated potential generated energy from this amount of potential biogas is 23.005 GW h/y. In total, there is possible energy generation from biogas equal to 38.468 GW h/y.

With the ESM based on current available data about energy consumption and RES potentials, three scenarios were performed. The first one is based on the usual scenario with the replication of the current situation in the Ormož municipality. The second scenario was performed for an 80% RES share in municipal energy consumption up to 2050, taking account of the EU decarbonisation target from the Energy Roadmap. The third scenario was set for a 100% RES energy supply.

In the following sub-sections, the energy sources used for covering energy needs in the three different scenarios are presented.

4.1. Business-as-usual scenario

The business-as-usual scenario (BAUS) is represented by the data for the current energy consumption in the Ormož municipality. The share of RES in the municipal energy balance is 26%. For heating purposes, the generated energy is taken in the following for specific sectors. The public sector requires 6.376 GW h/y and 78.1% of the energy is generated from natural gas, 15.2% from oil, 6% from LPG and 0.7% from wood biomass. This indicates a high potential, but also an urgent need to increase the share of RESs in the public sector due to the position of this specific sector, representing a form of role model for the other sectors. The energy consumption for heating the households is 46.479 GW h/y and the energy sources for the generated heat energy are wood biomass (61%), oil (24.4%), natural gas (13.5%) and LPG (1.1%). For the industry and service sector the heat-energy consumption is 55.928 GW h/y. The distribution of energy resources for heat-energy generation are follows: natural gas (97.2%), oil (1.6%), wood biomass (1.1%) and LPG (0.1%). This leads to a decision to increase the share of RESs in this sector by a large amount. The energy consumption for the public-transport sector is 0.682 GW h/y.

Electrical power is distributed from the grid, which in Slovenia has mix of different energy sources. The power is generated from coal (21.306 GW h/y), nuclear energy (19.214 GW h/y), RES (6.633 GW h/y), natural gas (2.335 GW h/y) and oil (0.084 GW h/y). In future scenarios, the objective is to increase the local energy independence. Consequently, the share of local electricity generation needs to be increased. This is also included in the next two scenarios. It is expected that due to the time horizon of following scenarios (year 2050) the technology will make substantial progress and that the cost for the RES technology will reduce, making it more accessible.

Fig. 6 presents the share of energy resources for electricity and heat generation in the BAUS.

4.2. 80% RES scenario

In the 80% RES scenario, the share of RES is increased with the objective being to achieve the optimal distribution of energy resources for energy generation from the economic and environmental points of view. The scenario proposes reaching an 80% share of RESs in the municipal energy balance, with the

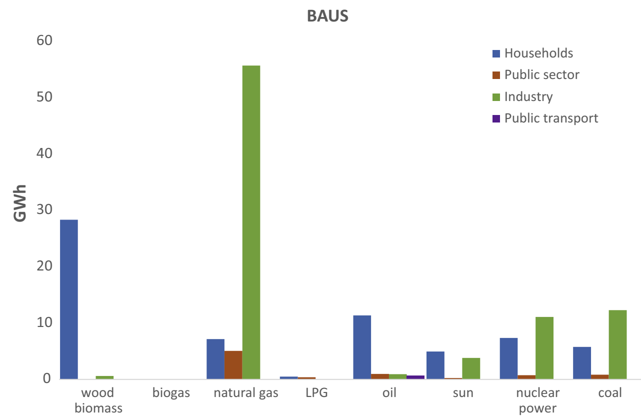

Fig. 6. Share of different energy resources for the energy consumption per sector in the Ormož municipality for the BAUS.

distribution of energy generation from the different resources being as follows: 43.500 GW h/y from wood biomass, 32.037 GW h/y from biogas, 26.227 GW h/y from the sun, 2.136 GW h/y from natural gas, 16.449 GW h/y from nuclear fuel and 6.881 GW h/y from coal.

Fig. 7 shows the shares of energy resources for energy generation in all the sectors for the Ormož municipality in the 80% RES scenario.

4.3. 100% RES scenario

The 100% RES proposes that the entire municipal energy supply is based on RES and the local energy self-sufficiency. Therefore, only the different types of RESs were included in the optimisation. The optimal scenario for the 100% RES share (see Fig. 8) is as follows: energy generated from wood biomass (46.000 GW h/y), from biogas (37.900 GW h/y) and from the sun (43.327 GW h/y). The geothermal, hydro and wind resources do not have sufficient potential for effective deployment in the Ormož municipality.

5. Environmental impact

The ESM highlights the importance of the environmental aspect. Therefore, an LCA impact assessment is provided within the model. The environmental assessment was performed using the LCA software package GaBi®, which was connected to the ESM, to provide the environmental evaluation. In the BAUS, the LCA impact categories are presented in Fig. 9. The highest share comes from the Global Warming Potential (GWP), which

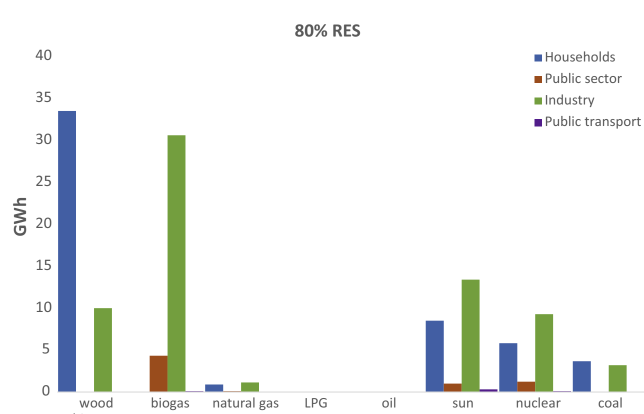

Fig. 7. Share of different energy resources for the energy consumption per sector in the Ormož municipality in the 80% RES scenario.

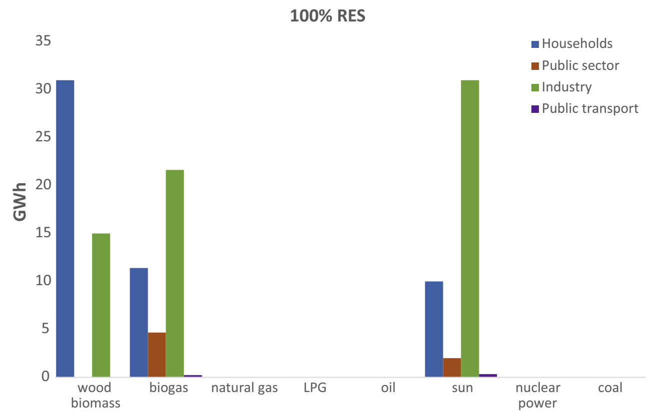

Fig. 8. Share of different energy resources for energy consumption per sector in the Ormož municipality in the 100% RES scenario.

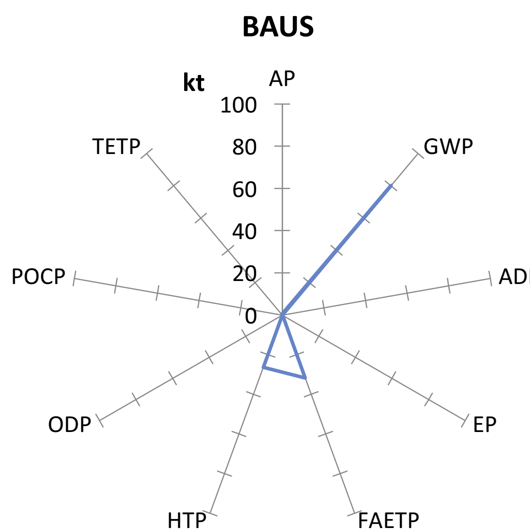

Fig. 9. LCA impact assessment of energy generation in the Ormož municipality for the BAUS.

represents the climate-change effects [43]. Therefore, it is crucial to have an impact on this category with actions such as energy-efficiency measures and RES integration, as presented in the following scenarios.

The definition of emission categories and the units used for each impact category in the next four figures are as follows [43]:

- ADP – Abiotic Depletion refers to the exhaustion of natural resources such as iron ore or copper, which are regarded as non-living. The impacts considered were those derived from the extraction of minerals and fossil fuels.
  [kt antimony eq./municipal energy consumption].
- AP – Acidification Potential – Acidifying pollutants have a variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems, and materials (buildings). The major acidifying pollutants are SO2, NOx, and NHx.
  [kt SO2 eq./municipal energy consumption].
- EP – Eutrophication Potential covers all potential impacts of excessively high environmental levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems.
  [kt PO4 eq./municipal energy consumption].
- FAETP – Freshwater Aquatic Eco-toxicity Potential refers to the impacts of toxic substances on freshwater aquatic ecosystems.
  [kt 1,4-dichlorobenzene eq./municipal energy consumption].
- GWP – Global Warming Potential represents climate change effects resulting from the emissions of CO2, methane, and other GHGs, into the atmosphere.
  [kt CO2 eq./municipal energy consumption].
- HTP – Human Toxicity Potential this impact category covers the impacts on human health of toxic substances present in the environment.
  [kt 1,4-dichlorobenzene eq./municipal energy consumption].
- MAETP – Marine Aquatic Ecotoxicity Potential represents the impacts of toxic substances on marine ecosystems.
  [kt 1,4-dichlorobenzene eq./municipal energy consumption].
- ODP – Ozone Layer Depletion Potential refers to the thinning of the stratospheric ozone layer as a result of anthropogenic emissions.
  [kt CFC-11 eq./municipal energy consumption].
- POCP – Photochemical Ozone Creation Potential refers to emissions of hydrocarbons and nitrogen oxides into the environment resulting in an increased potential for smog.
  [kt ethylene eq./municipal energy consumption].
- TETP – Terrestrial Ecotoxicity Potential covers impacts of toxic substances on terrestrial ecosystems.
  [kt 1,4-dichlorobenzene eq./municipal energy consumption].

The LCA impact categories for the 80% RES scenario are presented in Fig. 10. The GWP still has the highest share among the other impact categories. However, the values in comparison to those in the BAUS for GWP decreased by 84.64%. This indicates the enormous positive impact on the environment and the mitigation of the consequences of climate change.

The LCA impact categories for the 100% RES scenario are presented in Fig. 11. In this scenario, the HTP impact category has higher values than the GWP. The GWP also decreased in comparison to the values in the 80% RES scenario by 58.34%.

The results justify the designing of sustainable energy systems and, consequently, reducing the harmful impacts on the environment. Fig. 12 shows the environmental impact assessments for all three scenarios (BAUS, 80% RES and 100% RES).

As indicated before, the highest values among the impact categories come from the GWP, HTP and FAETP. The impacts decrease

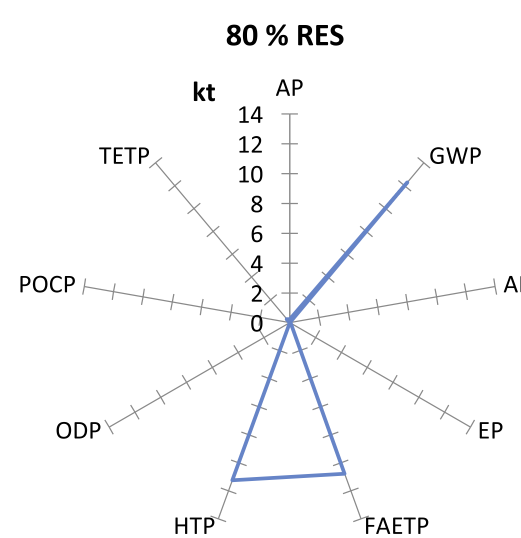

Fig. 10. LCA impact assessment of energy generation in the Ormož municipality in the 80% RES scenario.

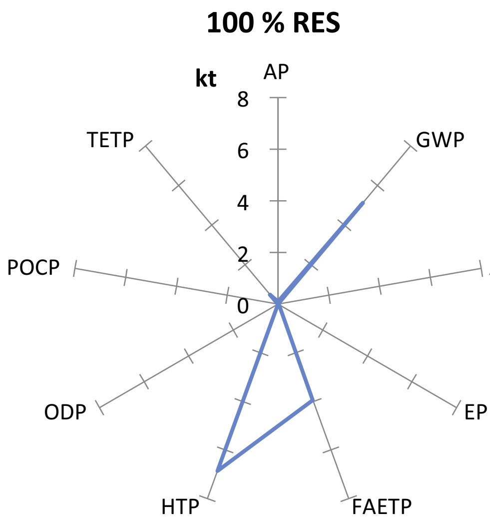

Fig. 11. LCA impact assessment of energy generation in the Ormož municipality in the 100% RES scenario.

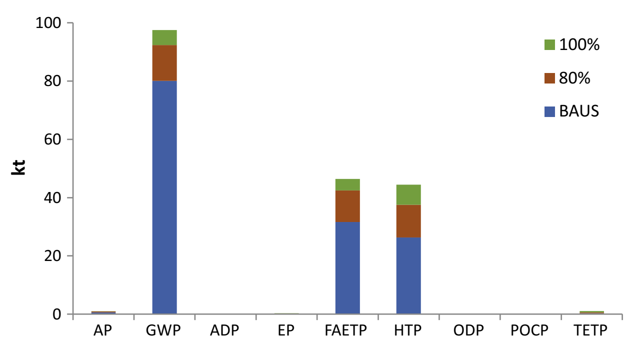

Fig. 12. Comparison of environmental impact categories among BAUS, 80% RES and 100% RES.

with respect to the share of RES in the scenarios. This means that the 100% RES has the lowest values regarding impacts on the environment. With this environmental analysis it is clear that the requirements when designing sustainable energy systems involve increasing the share of RESs in the energy balance.

6. Discussion

Energy and environmental policies demand sustainable development, and the objective of the European Roadmap is an 80% reduction in GHG emissions by 2050 [44]. Therefore, the natural energy systems will become more significant and the transformation pathway needs to be outlined. The development of the ESM represents an initial transformation activity. The bionic discipline was added during the model's development by proposing an optimal structure for the model and emulating the organisation in swarm groups. Therefore, a suitable optimisation method was depicted by emulating natural patterns. However, the bionic field is only in the initial phase of development and it is necessary to pursue research in this direction. In addition, it could generate the optimal solution because of the evolution process. The impact of the ESM is in accelerating the transformation process from fossil-oriented energy systems to more natural ones. Consequently, it contributes towards increasing the quality of the environment, a decrease in energy use and encourages the use of local renewable energy sources. Based on these actions the entire self-sufficiency of energy systems could be achieved. On the other hand, with the integration of bio-inspired elements into the development of the model, the bionic discipline was extended and useful added value was contributed. The impact of the ESM has an applicative aspect, while the model can be used in the initial planning phase of various energy projects. The ESM is a valuable tool for developing sustainable municipal energy systems. It is thought best to use the newly developed model in the case of municipal energy systems when preparing the local action plans. In the past, there was a problem with data quality and inconsistencies within the planning process. Compared to [13], where at different levels the relevant mathematical models are obtained and various optimisation approaches can be used, in the ESM there is only one level with mathematical models for all of the considered parts. For example, to be able to evaluate the efficiency of the symbiotic exchanges in the EIP using the ESM, it would require the combining of the obtained surrogate mathematical models for symbiotic exchanges, and then consider this complex model with the use of an evolutionary optimisation approach. This is more relevant in the search for a global optimum, since a multi-level approach might find a sub-optimal solution, while not considering all the interdependent constraints and objectives concurrently.

Therefore, the ESM is more valuable for use in municipal energy systems. The model could give great support to local energy agencies that manage energy issues in Slovenian municipalities. There are also local energy agencies across Europe (around 380 of them), which may find the ESM to be useful in their energy calculations. The model provides an in-depth analysis of the energy and environmental state in a specific geographical area. While the bio-inspired ESM presents the starting point in the development of the energy bionics field, the model would provide a significant contribution to the model for accelerating the development of the bionic energy discipline. Therefore, it could be used in research activities, workshops, and seminars for students, researchers and companies.

The ESM could have an important impact on policy implications if used by decision makers for future energy planning. The scenarios were calculated with respect to EU policy, more specifically the EU Roadmap to 2050, where a target of an 80% decarbonisation of energy systems is set. This is covered by the 80% RES scenario. The municipalities in general did not set targets to 2050. They have tended to establish energy action plans to 2020. In the future municipal energy planning, the ESM could impact on policy by calculating various scenarios with different parameters in accordance with EU and national policies, decision makers, resource availability, technology advancements and financial resources. The ESM could have policy implications in the field of energy efficiency and in the sector for renewables. There may also be possible contributions to the sector-specific policy measures, such as for transport, industry, public and household. Also, with environmental assessments of the scenarios results, there is an impact on environmental policy at the municipal level. Municipalities have environmental protection programmes in which measures for future time periods in different environmental categories are defined. With the 80% and 100% RES scenarios there could be a huge contribution minimizing the GWP in comparison to the BAUS. In accordance with this, the mitigation of climate-change consequences would be accomplished and other targets in the environmental programme would be met.

7. Conclusion

Sustainable development requires a decrease in energy consumption, especially from non-renewable resources, and an increase in the use of locally available energy resources. In the Ormož municipality, with 25,128 m^3/y biomass availability, 6,411,359 m^3/y biogas availability as well as energy from the sun, there is enough potential to establish a purely RES energy system. Recently, research has considered nature-inspired energy systems.

With the implementation of the ESM the knowledge of an advanced self-organising methodology into the field of natural energy systems is further expanded. The ESM could represent a valuable tool to develop sustainable energy systems, and will allow the automatic development of the most suitable and sustainable energy systems based on the local availability of energy sources.

To further improve the speed of the optimisation process, the use of a self-adaptive approach is proposed, in which the control parameters of the optimising algorithm are set automatically [45]. Additionally, when several new constraints and vague objective priorities arise, multi-objective approaches should be considered, like the Indicator-Based Evolutionary Algorithm, which is able to handle several contradictory objectives for which many classic multi-objective approaches are inappropriate [46].

As part of the case study, three scenarios were calculated for energy consumption in the Ormož municipality. Initially, the BAUS was performed, representing the current energy consumption in the municipality. In the other two scenarios, the 80% and 100% shares of RES for the energy generation were taken into account up to 2050. The results justify the viability of the presented scenarios due to the sufficient availability of natural resources and also due to the very long time horizon to accomplish the proposed scenarios by 2050. There is also a possibility to achieve the 80% RES in the municipal energy balance even sooner, and the 100% share soon after, although this is very dependent on the economic situation, the political will of decision makers and other end-users in the sector. However, the technical feasibility has been proven and the energy potential from RES is estimated to be high enough to cover the energy needs in the Ormož municipality for the 80% and 100% RES scenarios. The objective of the presented research was to prove the technical feasibility and show positive results for mitigating the consequences of climate change. However, in subsequent research work, an in-depth economic assessment should be conducted, because without national support schemes for integrating RES it is hard to envisage a substantial switch to renewable resources. While the time horizon in the proposed scenarios is up to 2050, it is necessary to also look at the technological advancements contributing to a decrease in the costs of RES technologies. If there is a substantial decrease in costs, it should be possible to implement the proposed scenarios without higher subsidies.

Regarding the environmental evaluation of the scenarios; it is important to highlight the enormous impact of the 80% and 100% RES scenarios on reducing the Global Warming Potential. In future work, the footprints [47] should also be calculated for the 80% and 100% RES scenarios in order to achieve a more objective environmental assessment and pay attention to the trade-offs among the assessed categories [48], which the footprints also represent.

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