ReEnAct II: Regionale Energiewende Aktiv gestalten

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Abstract:

This paper follows the research conducted within the ReEnAct project, building upon the previous work and further advancing the findings and insights developed through the initiative through the exploration and utilization of renewable energy potential in the Penetal/Loitz region. It refines and extends the application of the STEMP-tool, with significant enhancements focused on integrating linear optimization and relying predominantly on oemof tools. The study broadens the scope from merely solar and wind energy to include biomass and innovative floating PV installations for swamps and moorlands. The primary goal remains to mitigate carbon emissions and foster sustainable development in the region. In alignment with Germany's energy transition and the German Climate Change Act, this research contributes to national objectives by advancing the adoption of renewable energy and reducing greenhouse gas emissions. The energy transition highlighted in this study serves as a model for successful renewable energy integration in rural areas, driven by local initiatives, ambitious targets, and supportive policy frameworks. This paper introduces an improved digitalized model that enhances data organization and efficiently manages large annual datasets, transitioning from district-level analyses to comprehensive city-wide assessments in a single operation, surpassing the previously developed Stemp-tool that depended on average estimations for renewable energy potential assessment.

Keywords:

ReEnAct project, STEMP-tool, Renewable energy potential, Sustainable development, Energy transition, Optimization Scenarios, Energy system modeling, Optimization tool.

Introduction

Germany's shift to sustainable energy marks a key transformation in its power strategy. The country aims to cut back on fossil fuels and bring more green energy into its power system [1]. This move develops national plans, like the German Climate Change Act [2]. This law seeks to lower greenhouse gas emissions and boost green growth in all parts of society. Country areas such as Penetal/Loitz have a huge role in this change. These places have Spaciousness potential to attain green power through sun, wind, plant-based fuel, and other green power methods [3].

This paper builds upon the research conducted within the ReEnAct project [4], a pioneering initiative focused on optimizing energy systems in the region of Penetal/Loitz. By exploring and utilizing the renewable energy potential in this area, the research aims to contribute to Germany’s broader climate and energy goals [5], offering valuable insights for regions with similar energy landscapes. While previous studies have laid the groundwork for renewable energy integration in rural areas, this study expands on those findings by refining and enhancing the tools and methods used for energy potential assessment, specifically the STEMP-tool [6].

The STEMP-tool, initially designed to assess renewable energy potential at the district level, is upgraded to include linear optimization techniques, relying on the open-source energy modelling framework, oemof tabular [7]. This enhancement allows for a more granular, efficient, and accurate approach to assessing renewable energy potential, moving beyond simple estimations to incorporate sophisticated optimization models that consider factors like energy demand, supply, and system flexibility.

This study's main objective is to cut carbon emissions and promote sustainable growth in the area utilizing cost-optimized methods. This study fits with Germany's shift in energy use [8], which seeks to eliminate emissions from the energy field while assuring renewable energy systems are cost-effective and feasible [9]. By improving the use of the STEMP-tool and adding modern technologies, this study helps meet national goals [10]. It offers direct answers and a model that can grow for bringing renewable energy to rural parts all over Germany.

Furthermore, this paper introduces a newly digitalized model designed to improve data organization and management, facilitating the transition from district-level to city-wide assessments in a swift operation. By refining data processing techniques and incorporating large datasets, the enhanced model surpasses the original STEMP-tool, offering more accurate insights into renewable energy potential across broader geographical scales.

Project Overview

The primary objective of this project is to further enhance the capabilities of the existing STEMP-tool by incorporating recent technologies and optimization strategies. This development aims to not only improve the accuracy and flexibility of energy assessments but also provide more comprehensive solutions for renewable energy integration in the Penetal/Loitz region and all urban areas surrounding it. By introducing a range of innovative technologies and optimization techniques, the tool can adapt to a broader set of scenarios, giving room to display detailed calculations and offer more robust insights into potential energy systems.

To accomplish this, the tool's capabilities were expanded with an emphasis on increasing optimization options. By integrating technologies [11] such as biomass energy production, floating photovoltaic (PV) installations for swamps and moorlands, and leveraging advanced linear optimization techniques primarily using the oemof framework, the tool’s potential for analysing and optimizing renewable energy systems were significantly improved [12]. These enhancements allow for more precise and scalable energy assessments, helping to align the tool with the evolving needs of energy planning and sustainability goals.

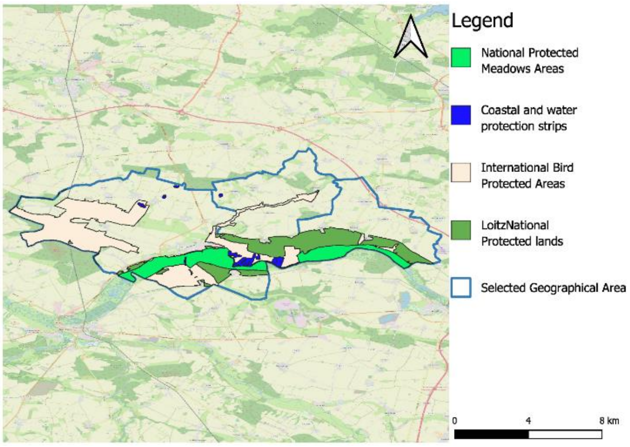

Figure 1 Protected areas in the region [13].

A significant development in this project is the integration of constraints for protected areas [14], which limits the expansion of renewable energy installations, particularly floating PV systems on peatland and wind farms in bird-protected areas. These protected areas are crucial for biodiversity and conservation efforts, and they restrict the potential for large-scale renewable energy deployment in these zones [15]. As a result, the tool now accounts for these limitations by reducing the available potential for renewable energy projects. This constraint narrows the feasible options for renewable energy expansion in certain regions, leaving small potential for improvement. By considering these environmental and regulatory factors, the tool utilizing QGIS [13] becomes more aligned with real-world conditions assessed through open street maps [16], ensuring that the proposed solutions are both technically feasible and legally permissible.

In addition to the technological upgrades and environmental constraints, this project includes the development of several key scenarios to explore different future energy pathways for the region. These scenarios are designed to represent a variety of outcomes based on different energy strategies and assumptions about future conditions. The First scenario is named Business-as-Usual which serves as a baseline, showing What may result if the current energy policies and practices were maintained without any significant changes. This scenario assumes no new renewable energy integration, and no shifts in technology or policy. It provides a reference point for evaluating the effects of more proactive energy strategies.

The second scenario is the Self-Sufficiency scenario which explores sustainability in the region becoming more self-reliant for its energy needs, relying primarily on local renewable resources. The aim of this scenario is to produce enough energy and utilize energy storage to meet the current demand for the city without abiding with the European regulations or goals [17]. The objective of this scenario is to achieve energy independence while ensuring sustainability and resilience. This scenario illustrates the potential for urban energy systems, offering insights into the feasibility and benefits of decentralized energy production in rural areas.

Moreover, the Cost Optimization scenario was introduced seeking to minimize the overall cost of energy production while still meeting sustainability targets [18], examining how different energy technologies and configurations can be combined to create the most cost-effective renewable energy system for the region according to levelized cost of energy or feasible investment costs. The scenario is valuable for identifying cost-effective strategies that reduce reliance on expensive energy imports and promote more affordable, locally sourced energy solutions.

Finally, in line with the EU's ambitious climate goals [19], the No-Emissions scenario investigates achieving net-zero carbon emissions. This scenario explores the technical and economic viability of transitioning to an entirely emissions-free energy system in the region, utilizing the added renewable energy sources and eliminating energy imports to the city. By aligning with the EU’s climate targets, this scenario provides valuable insights into how rural regions can contribute to national and international climate action, while also ensuring economic growth and energy security.

The process of defining these scenarios involved thorough consideration of local energy demands, available resources, and the region's specific goals for carbon reduction and sustainability and reflecting the newly calculated maximum potential for renewable energy. Each scenario was developed in the enhanced STEMP-tool, which allows for detailed simulations, scenario comparisons, and optimization of energy systems. By incorporating these scenarios, the tool can provide actionable insights that can influence future energy policy and development.

Methodology

This study focuses on further developing and refining the STEMP-tool by incorporating advanced optimization techniques, expanding its technological scope, and introducing a new user interface to make the tool more accessible, efficient, and applicable to real-world energy challenges. The methodology adopted in this study emphasizes the integration of these enhancements while utilizing modern tools to facilitate energy modelling, optimization, and scenario analysis [20].

Previously, the tool relied on pure Python [21] for its features and models. However, to improve development, productivity, and adaptability, Jupiter Notebook [22] was introduced as the primary platform for running and validating the model's code and results. Jupiter Notebook allows for more efficient coding, making the process more reliable and transparent. It enables actions to be written down, results to be visualized, and changes to be made as progress is made. Additionally, it facilitates collaboration among team members, allowing them to work together, analyse and fix issues more efficiently, and present results with text, code, and visuals all in one place. This shift to Jupiter Notebook also streamlines the workflow, making it more organized and continuous, while improving the documentation process by explaining the ideas and methods behind each version of the model.

To improve the optimization capabilities of the tool, linear optimization techniques were integrated into the model [23], which allows for more accurate and efficient energy system simulations. Utilizing Pyomo [24, 25] linear optimization plays a key role in determining the most effective and sustainable energy solutions by minimizing or maximizing specific objectives, such as energy costs, emissions, and system reliability, while adhering to a set of constraints, such as energy demand [26], resource availability [27], and technological limitations [28].

Several solvers are employed for the optimization tasks, including CBC (Coin-or branch and cut) [29], a widely used solver for mixed-integer linear programming (MILP) problems. CBC is known for its efficiency and speed in solving large-scale optimization problems, making it an ideal choice for energy systems that require the consideration of multiple variables and constraints. Additional solvers are also used to compare results and ensure robustness in the optimization process, helping to identify the best configurations of renewable energy technologies and system parameters, based on the objectives and constraints defined for each scenario.

In addition to optimization enhancements, the model now incorporates protected areas that limit the expansion of renewable energy technologies. the use of floating photovoltaic (PV) on peatland and wind energy in bird-protected areas are now restricted. These constraints significantly reduce the available land for energy generation, leaving limited potential for improvement.

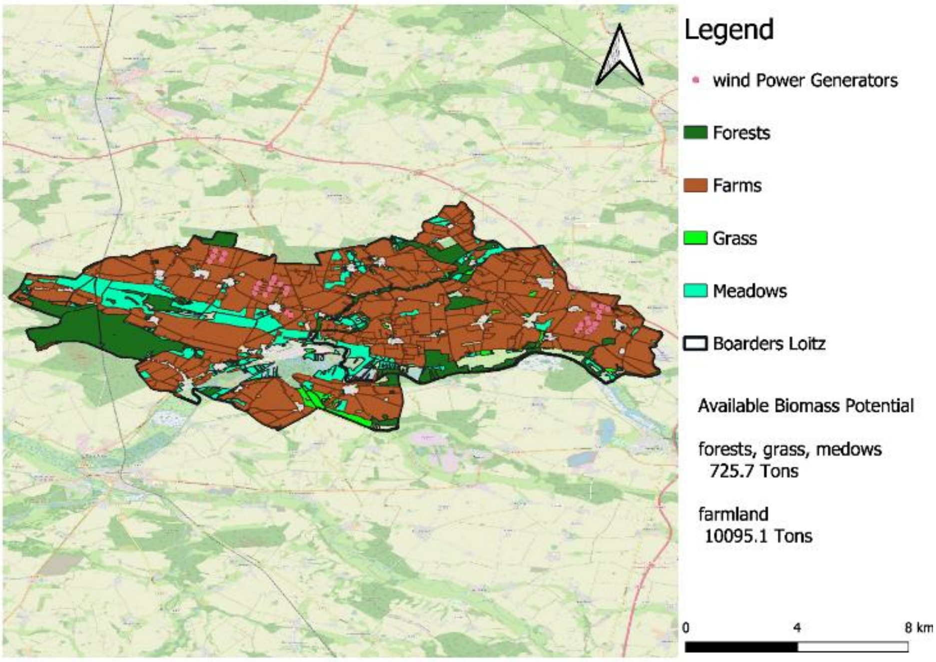

Figure 2 Map of the new incorporated technologies potential locations [13]

The tool's capability to model and optimize energy systems has been significantly expanded to include new renewable energy technologies. Among these are Biomass energy production [30] which was integrated as a sustainable and versatile source of power. The tool now models the potential of biomass, considering its availability, conversion technologies, and integration with other renewable resources. Additionally, Floating PV [31] installations are now incorporated into the model as well, particularly for use in swamps and moorlands where land-based solar panels may not be feasible. The tool evaluates the technical and economic potential of floating PV systems in water bodies, considering the constraints and benefits of this innovative technology. Finally, Agri-PV, which integrates solar energy generation with agricultural activities, is another technology now modelled in the tool. This system allows the dual use of land for both solar power generation and farming, offering a sustainable solution to land-use conflicts and increasing overall land productivity. The tool simulates the optimal configuration of Agri-PV systems based on factors like crop types, solar panel efficiency, and land availability.

These recent technologies complement the existing renewable energy sources like solar and wind, expanding the tool's ability to provide more comprehensive assessments of energy systems and their potential for integration into both rural and urban landscapes [32].

The energy data used in this study was extrapolated from the MV region (Mecklenburg-Vorpommern) and then interpolated to match the size and characteristics of the Penetal/Loitz region. Initially, detailed energy consumption, demand, and renewable energy generation data were available for the broader MV region [33]. This data was then extrapolated to represent the specific energy needs and potential of the Penetal/Loitz region, considering factors such as population density, industrial activity, and local climate conditions.

Once the data was extrapolated, interpolation techniques were applied to adjust and scale the data according to the geographical and socio-economic characteristics of Penetal/Loitz. This process ensured that the model accurately reflects the energy dynamics of the target region, even in the absence of direct data specific to Penetal/Loitz. By interpolating this data, we were able to create a more tailored model that better represents the energy system of the region and provides reliable insights for planning and decision-making.

Alongside the improvements made in optimization and modelling, a new user interface is currently under development by RLI to make the STEMP-tool more user-friendly and accessible to a broader audience.

The interface is designed with an emphasis on simplicity, ease of use, and intuitive navigation, allowing users—from energy planners to everyday citizens—to interact with the tool without requiring deep technical knowledge of programming or optimization algorithms.

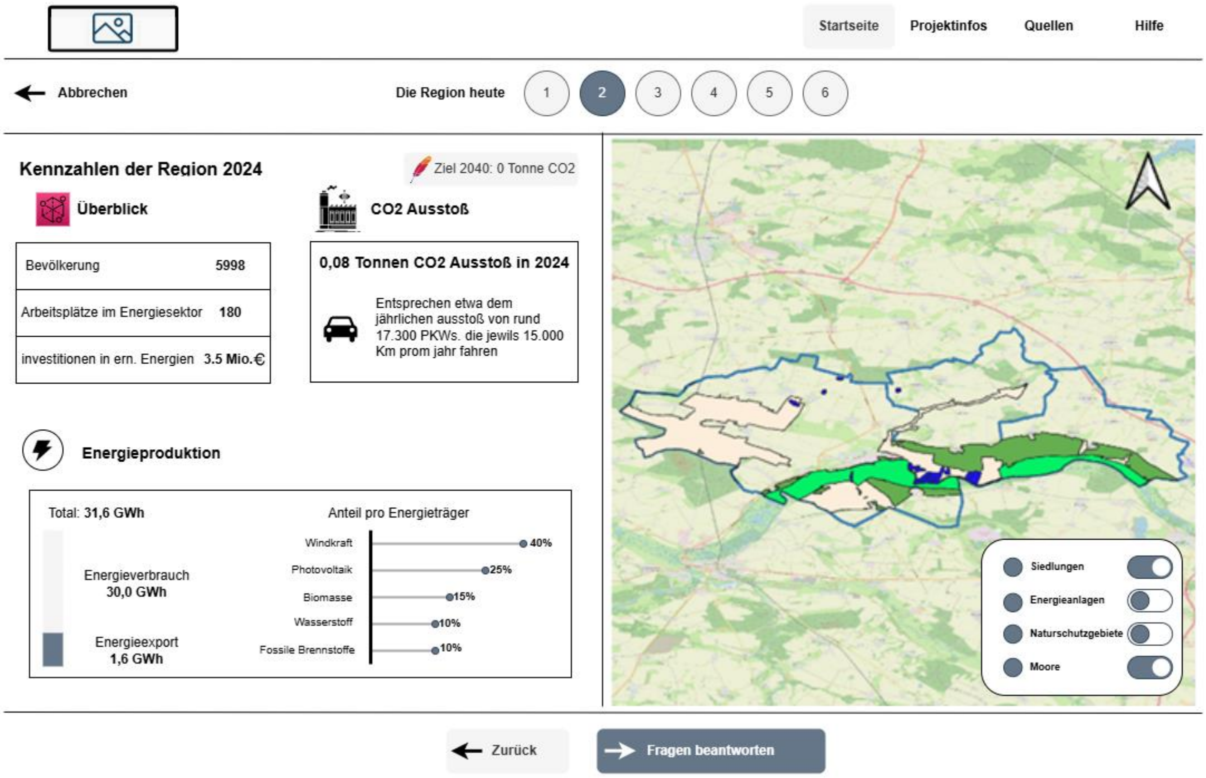

Figure 3 Concept for the User interface platform.

The interface is intended to present the results of complex calculations and optimizations in a clear and easily understandable format, using visual aids such as charts, graphs, and maps to effectively convey insights. Additionally, users will be able to adjust input parameters with ease, explore different scenarios, and evaluate the potential outcomes of their decisions within a dynamic, user-centric environment. By making the tool more accessible, the aim is to empower local governments, energy professionals, and stakeholders to model and optimize energy systems for both cities and rural areas, while capturing the social impact of such projects. This includes accounting for public agreement or opposition to specific energy practices and policies.

Urban energy systems are increasingly recognized as essential components of a sustainable future, as they enable efficient integration of renewable energy, grid management, and carbon reduction efforts [34]. The development of a user-friendly interface will be a critical step in making urban energy modelling and optimization more widely adopted and understood, contributing to the transition toward low-carbon urban environments.

As mentioned in the project's overview the tool also includes the capability to run scenario analysis and simulate various energy configurations. By leveraging advanced optimization algorithms, users can explore multiple potential futures, including those focused on renewable energy integration, cost optimization, and emission reduction. Through the ability to explore different scenarios, the tool helps urban planners assess the feasibility of renewable energy integration in cities, evaluate the economic viability of various energy solutions, and explore strategies to reduce greenhouse gas emissions [35].

The adaptability of the tool to both rural and urban energy systems make it a versatile model for future energy planning and policy development, bridging the gap between theoretical models and practical implementation.

The methodology employed in this research reflects a commitment to improving both the technical and user-facing aspects of the STEMP-tool. By transitioning to Jupiter Notebook, incorporating linear optimization with powerful solvers like CBC, integrating environmental constraints such as protected areas, adding new renewable energy technologies like biomass, floating PV, and agrivoltaics, and developing a more accessible user interface, the tool is being made not only more impactful but also more applicable to real-world energy challenges. The enhanced STEMP-tool enables users to explore renewable energy integration and optimization across various scenarios, offering valuable insights into the sustainable development of urban energy systems.

Results & Discussion

The enhancements made to the STEMP-tool have led to substantial improvements in both its technical performance and its usability for various users. This section presents the findings from the application of the updated tool, examining the impacts of these improvements across different energy scenarios. Each scenario's results are explored in detail, showing how the tool's advanced optimization capabilities, recent technologies, and user interface updates contribute to better energy system simulations.

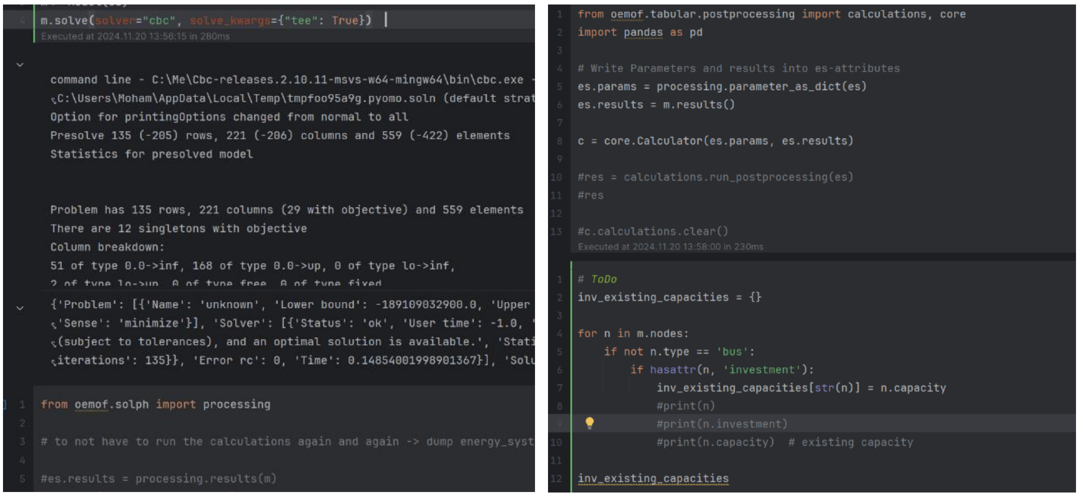

Figure 4 Snaps from the newly developed code [6].

Illustrated in Figure 4, Following the integration of linear optimization techniques and new renewable energy technologies, the tool's ability to manage large-scale, complex energy systems was significantly enhanced. The core optimizations, powered by solvers like CBC (Coin-or branch and cut), enabled the tool to evaluate energy configurations more efficiently. These modifications were carefully validated through the execution of several energy system simulations, focusing on the tool's ability to provide realistic and actionable insights.

The initial testing phase incorporated both conventional and novel renewable energy sources such as biomass, floating PV, and agrivoltaics. The optimization results from this phase demonstrated improved capacity for accurately modelling energy generation and cost optimization, highlighting the benefits of these recent technologies. The inclusion of biomass and floating PV systems, along with solar and wind, created more sustainable and diversified energy configurations.

To assess the impact of the tool's modifications, four distinct scenarios were modelled. Business as Usual (BAU), Self-Sufficiency, Cost Optimization, and Emission-Free. The following sections detail the results obtained from each of these scenarios, highlighting the contribution of each renewable energy source and evaluating the overall feasibility of the energy systems modelled.

The Business as Usual (BAU) scenario serves as the baseline for comparison. It simulates the continuation of current energy trends without intervention or investment in new technologies. The energy mix under this scenario remains primarily reliant on traditional solar and wind energy sources. The results, shown in Figure 5, indicate that the lack in meeting demand locally and relying on imported electricity, due to land-use and regulatory constraints.

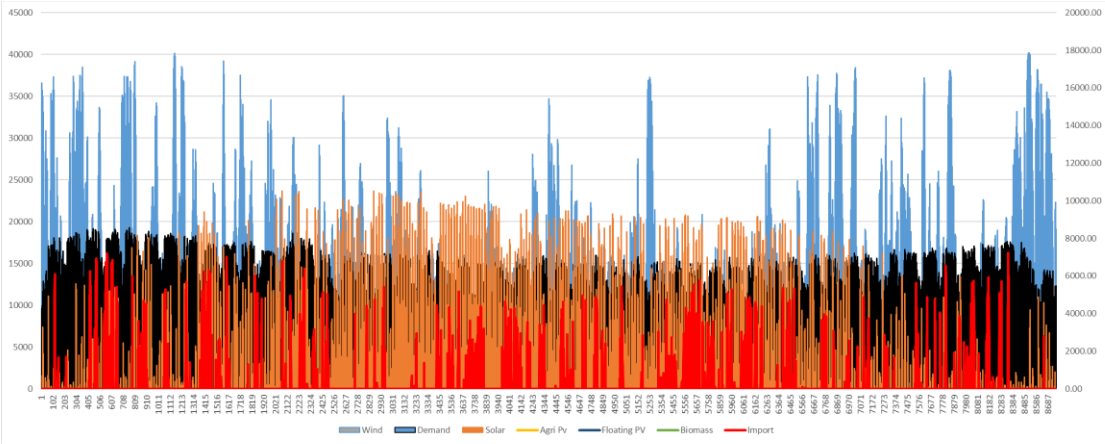

Figure 5 Business as Usual scenario results [6].

Figure 5 displays the energy generation contributions across different technologies, illustrating that while wind and solar provide most energy, import fills in the deficit with biomass and floating PV with no contributions. The cost and emissions associated with this scenario were also higher compared to the other scenarios, as the energy mix relies heavily on the current infrastructure and limited technological innovation.

In the Self-Sufficiency scenario, the goal is to achieve energy independence for the Penetal/Loitz region through local renewable energy generation. This scenario was designed to optimize the use of available renewable resources including solar, wind, biomass, and floating PV systems while minimizing reliance on external energy imports. The results, presented in Figure 6, demonstrate that the region could meet its energy needs with locally sourced renewable energy.

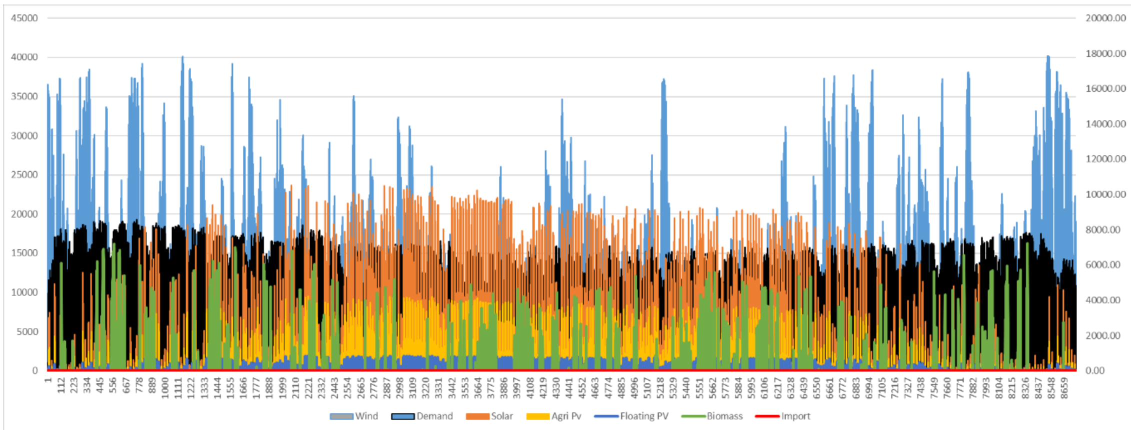

Figure 6 Self Sufficiency scenario results [6].

Figure 7 shows the optimized energy generation for this scenario, where floating PV and biomass play a significant role in supplementing solar and wind energy. This setup ensures that the energy demand is consistently met, even during periods of low solar or wind generation. Economic analysis reveals that although initial infrastructure investments are higher, the long-term savings from reduced dependency on external energy sources would make this configuration highly cost-effective.

The Cost Optimization scenario aimed at achieving the most cost-effective energy solution while ensuring the system met sustainability goals. The optimization algorithm was applied to identify the optimal mix of renewable energy sources, considering initial investment, operational costs, and system maintenance.

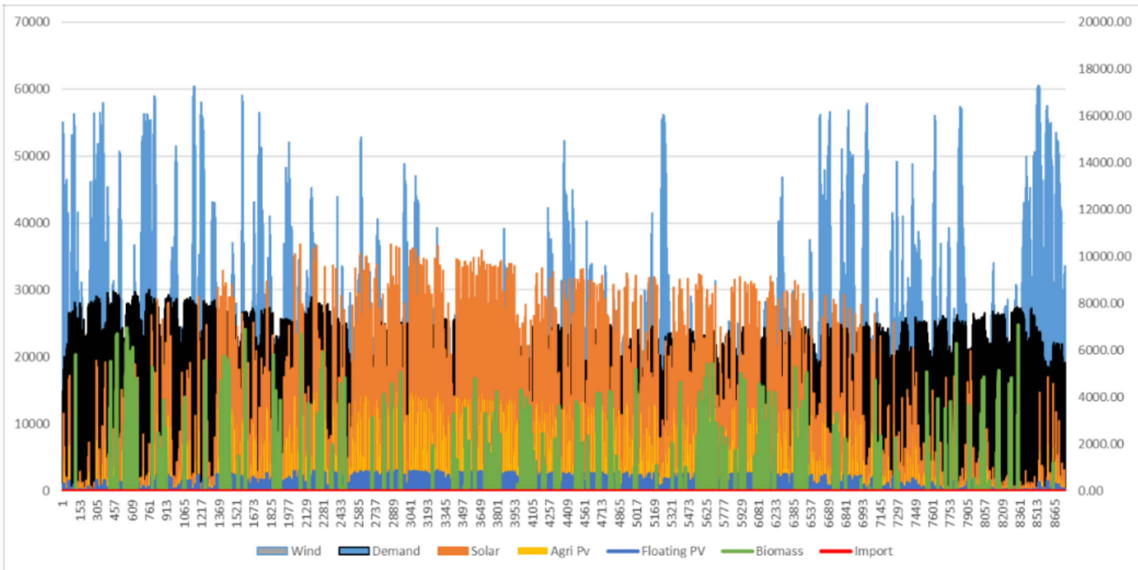

Figure 7 Cost Optimization scenario results [6].

Results from this scenario, illustrated in Figure 8, show that the addition of floating PV and Agri PV provides a cost-effective solution when compared to relying solely on solar and wind energy. The tool optimized the energy mix to reduce overall costs by maximizing the use of resources like Agri PV, which offer higher energy yields in specific conditions. This scenario highlights the cost-benefit ratio, demonstrating that, while initial costs for technologies like floating PV and Agri-PV are higher, the long-term operational and maintenance savings significantly outweigh the initial investment.

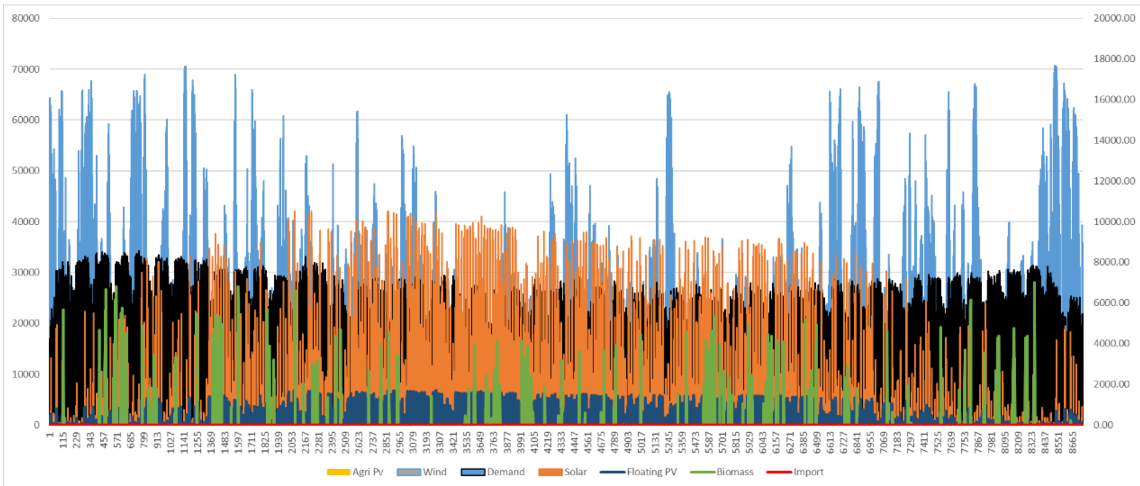

Figure 8 Emission Free scenario results [6].

The Emission-Free scenario was modelled to achieve net-zero emissions by integrating renewable energy sources while eliminating carbon emissions associated with energy production. The results, presented in Figure 8, demonstrate how an energy mix consisting solely of solar, wind, biomass, and floating PV can meet the region's energy needs without producing any greenhouse gas emissions. The incorporation of carbon capture technologies further enhances the emissions reduction potential.

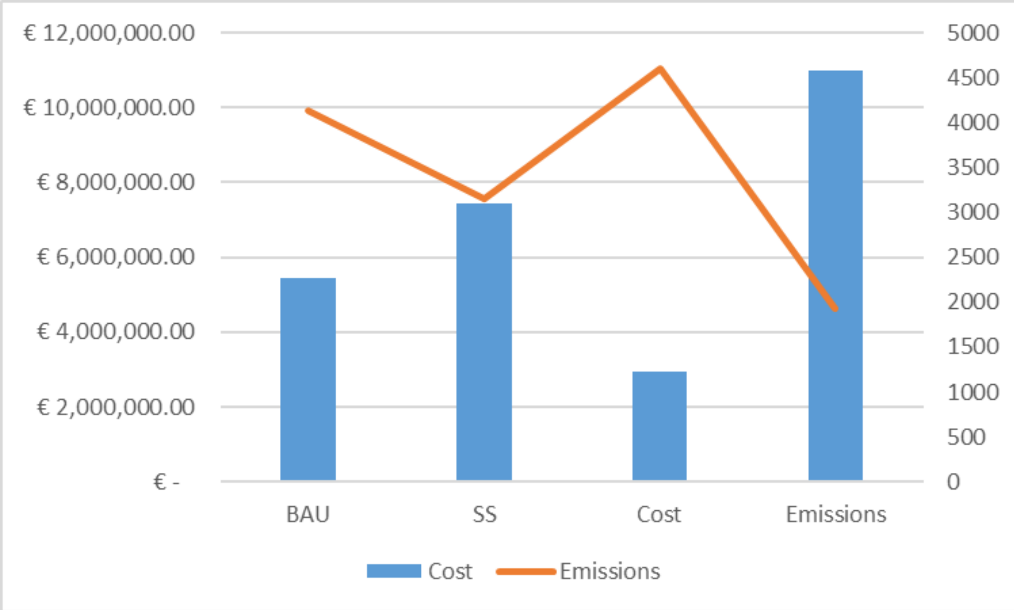

Figure 9 Different results for Scenarios [6].

Figure 9 shows a comparison between the emissions reductions and cost ratio associated with the different scenarios, confirming that the optimized energy mix can effectively meet the region's energy demand while achieving the EU's climate targets. The inclusion of floating PV, Agri PV and biomass, along with wind and solar, offers a balanced solution that satisfies both energy demand and emissions reduction goals.

The performance of the updated tool was assessed by comparing its results with extrapolated energy data from the Mecklenburg-Vorpommern (MV) region, which was then interpolated to match the specific characteristics of the Penetal/Loitz region. This process ensured that the data used for modelling was accurate and tailored to the region's unique energy dynamics.

The modified STEMP-tool has proven to be highly effective in simulating and optimizing energy systems for the Penetal/Loitz region. The results from the various scenarios highlight the tool's ability to integrate modern technologies and optimize energy configurations to meet different sustainability and cost objectives. The addition of biomass, floating PV, and agrivoltaics has significantly enhanced the tool's capacity to model diverse renewable energy systems, addressing land-use and environmental concerns while providing reliable, cost-effective solutions.

In particular, the Self-Sufficiency and Emission-Free scenarios demonstrate the potential of the tool to contribute to energy independence and climate action goals. The optimized configurations show that achieving energy independence through locally sourced renewable energy is feasible, and the tool offers an actionable framework for achieving net-zero emissions.

Furthermore, the Cost Optimization scenario features the importance of economic factors in energy planning. The ability to minimize costs while maintaining sustainability is essential for achieving long-term energy goals.

Conclusion

Development of the STEM-Tool was necessary, not only to improve the model's capacity to model and optimize the current energy systems but also to introduce new technologies and optimization scenarios to have different goals tailored to the interests of the different social groups in urban communities, furthermore the development of a friendly user interface will be a development in open-source tools evolving the tool in an efficient way and enabling it to do real change in the urban community and energy planning sector on a regional level.

The integration of linear optimization techniques, combined with CBC solver, has made it possible to evaluate energy configurations with greater accuracy and efficiency. In addition to including new technologies that are suitable to the urban city scale with the existence of agricultural land and peatland, it is eminent to consider newer technologies that these locations serve as a source for such as Floating PV, Agri PV, and Biomass offering a broader range for optimization and a broader vision tom the urban sector.

Various scenarios, including Business as Usual (BAU), Self-Sufficiency, Cost Optimization, and Emission-Free, were modelled to assess the impact of these enhancements. The BAU scenario highlighted the limitations of the current energy mix, which primarily relied on solar and wind. By contrast, the Self-Sufficiency scenario showed that, with the right configuration, the region could potentially meet its energy needs entirely through locally generated renewable energy. The Cost Optimization scenario demonstrated that while certain technologies like biomass and floating PV require higher initial investments, they offer long-term savings and contribute to system cost reduction. The Emission-Free scenario confirmed that integrating a mix of renewable energy sources, including carbon capture technologies, could meet EU climate goals and achieve net-zero emissions.

To ensure the reliability of the tool, the results were compared with extrapolated data from the Mecklenburg-Vorpommern (MV) region, adjusted for the specific characteristics of the Penetal/Loitz region. The model's outputs aligned closely with the expected trends, verifying the accuracy and applicability of the tool for regional energy planning.

The results published in this study highlights the important effect of fostering renewable energy with various technologies in the energy planning decisions especially in urban areas while addressing energy security and climate change. Granting the ability to simulate and optimize energy systems with a mix of renewable technologies to local urban stakeholders was always an objective for this project and now the tool can provide important insights into the potential for integrating these systems into regional energy grids. As renewable energy technologies and climate change acts and regulations continue to evolve this tool will always have room for improvement and the inclusion of further technologies and limitations to be always up to date and offer the potential to play a key role in guiding energy transition strategies and supporting sustainable energy policy development.

The Tools development is an ongoing process and future improvements will be focusing on the optimization algorithm and the development of the user friendly interface to allow the multiple parties in the urban society to interact with the tool and be a part of the discission making procedure without the need to be an expert in the energy field but just basic knowledge and visualization of results coupled with real-time data and dynamic simulations is more than enough to participate in the decision making.

In conclusion, the STEMP-tool has proven to be an invaluable resource for the modelling and optimization of renewable energy systems. The improvements made in this study lay the groundwork for future research and development in energy system optimization, offering crucial insights that can contribute to the transition towards a sustainable, low-carbon energy future.

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