

Article

Integrating Knowledge Acquisition, Visualization, and Dissemination in Energy System Models: BENOPTex Study

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Abstract: While storytelling and visualization have always been recognized as invaluable techniques for imparting knowledge across generations, their importance has become even more evident in the present information age as the abundance of complex data grows exponentially. These techniques can simplify convoluted concepts and communicate them in a way to be intelligible for diverse audiences, bringing together heterogeneous stakeholders and fostering collaboration. In the field of energy and climate research, there is an increasing demand to make sophisticated models and their outcomes explainable and comprehensible for an audience of laypersons. Unfortunately, traditional tools and methods may be inefficient to provide meaning for input and output values; therefore, in this study, we employ a storytelling tool, the so-called Academic Presenter, to digest various datasets and visualize the extended BioENERgy OPTimization model (BENOPTex) outcomes in different online and offline formats. The developed tool facilitates communications among collaborators with a broad spectrum of backgrounds by transforming outcomes into visually appealing stories. Although this study focuses on designing an ideal user interface for BENOPTex, the developed features and the learned lessons can be replicated for other energy system models.

Keywords: storytelling; data visualization; energy system models; information dissemination



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1. Introduction

As a consequence of the oil crisis in 1973, the International Energy Agency (IEA) launched a new program, intending to build the first detailed techno-economic energy system model for analyzing oil use options [1]. Since then, energy system models have become an indispensable part of the decision-making processes. Energy System Optimization Models (ESOMs) in the past have often been at the national level, focusing on the power sector with few renewable technologies (such as hydroelectric and geothermal power plants). These early attempts crudely modeled regions as nodes connected to others via trades while optimizing a single objective function (e.g., minimizing the total system cost). Although the previous generation of ESOMs enabled researchers to understand the underlying system, these streamlined models are considered outdated and incapable of addressing the complexity of real-world problems that policymakers have to confront today [2]. Unfortunately, these models often ignored social factors in their analyses [3], and many influential variables were either overlooked or oversimplified by assuming exogenous and external system boundaries (e.g., the competition over land). These shortcomings have driven practitioners in recent years to improve various aspects of these models in order to paint a more realistic picture [4–6].

Two particular dimensions of ESOMs are growing significantly: spatial and temporal resolution [7]. Aryanpur et al. [8] reviewed 36 multi-regional ESOMs from 22 countries and concluded that spatially resolved ESOMs provide substantial added value for regions with heterogeneous renewable energy potential, which can affect the results of the scenarios with

a high mix of Variable Renewable Energies (VREs). Thus, the need for spatially resolved models increases as the proportion of VREs increases. Scheller and Bruckner [9] reviewed various ESOMs with a high level of spatial, temporal, and contextual detail and concluded that future models should address six research challenges: spatial planning, temporal resolution, an integrated view, business modeling, complexity, and uncertainty analysis. Prina et al. [10] also reviewed 22 ESOMs, 9 of which are long-term models concerning resolution in time, space, techno-economic detail, and sector-coupling. The authors concluded that none of the reviewed models achieved a high resolution in all of these fields simultaneously. After comparing 40 open access energy system models, Oberle and Elstrand [11] concluded that the results of these models should not be compared with those of conventional energy system models due to their simpler technological and methodological designs. Henke et al. [12] conducted an explorative comparison of the region mapping between energy system models and the integrated assessment models and concluded that these two model types differ in the way they define regions.

Brosowski et al. [13] emphasized the importance of considering higher temporal and spatial resolutions for straw as a major bioenergy feedstock. Sadr et al. [14] demonstrate that by incorporating daily temporal resolution for agricultural residues and energy crops, we can endogenously account for the availability of processing facilities. Lehneis and Thrän [15] and Lehneis et al. [16,17] also developed simulation models, the so-called ReSTEP models where ReSTEP stands for Renewable Spatial-Temporal Electricity Production, to enhance the spatial and temporal resolution of the electricity generated from wind turbines and photovoltaic (PV) systems considering detailed plant and weather data.

The models developed in the energy field adopt different scales in spatial, temporal, economic, and technological dimensions to answer pertinent questions. For instance, the spatial scale of ESOMs generally is rather coarse at the country level, whereas the spatial scale of the distribution grid planning models can be as refined as a household. To enhance the spatiotemporal resolutions in ESOMs, Gong et al. [18] proposed a soft-coupling framework that combines the strengths of ESOMs and Power Sector Models (PSMs) for a more comprehensive assessment of VREs in the energy system transitions. A similar linking method between ESOMs and PSMs is pursued in [19,20], resulting in complex hybrid models. Hybrid models have to deal with the multi-dimensional granularity gaps that exist between models in different disciplines [21]; therefore, the next generation of hybrid ESOMs needs novel communication methods in order to assist stakeholders with heterogeneous perspectives in comprehending the underlying interdisciplinary system.

Storytelling can connect diverse stakeholders and foster collaboration and collective action [22]. Stories can induce change and showcase the transformation that might occur in communities [23]. In the field of energy and climate research, there is an increasing demand to detect relationships integrating various aspects of the problem using information visualization, where there are plenty of quantitative data [24]. Although information visualization can assist scientists in simplifying complex systems for the users, this task can become particularly challenging as the complexity of the data increases [25]. This is due to the fact that the human cognitive capacity for processing information is limited [26]. Therefore, applying storytelling techniques together with information visualization may be necessary to present outcomes efficiently. More importantly, storytelling can enhance building confidence in outcomes. Unfortunately, energy models have faced criticism for their perceived lack of objectivity [27]. In energy system modeling, modelers utilize scenarios to quantify corresponding variables in qualitative narratives; therefore, constructing a scenario can be seen as storytelling with numbers. However, only presenting scenarios without backstories can damage the trust in the results of these models.

Including data-intensive aspects in optimization, simulation and equilibrium models are often accomplished using databases, which provide no visual clues to users. While these databases are structured to be processed efficiently by machines, they are difficult for humans to interpret and verify. To overcome this problem, researchers employ numerous innovative techniques, such as the User Interface (UI). The Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) is a well-known pioneer ESOM that was developed in the early 1980s by IIASA [28]. MESSAGE uses a command line interface to read data in GAMS data exchange (GDX) file format. In 2019, the developers extended the original model in MESSAGEix by incorporating an online web-based user interface to facilitate the integration of data sources and methodologies across disciplines [29]. In the Renewable Energy Mix (REMix) model, modelers developed an interface that generates scenarios using a branching method for multiple regions. To minimize human effort in their design, technologies can inherit the basic properties of their parent technologies while adjusting themselves for the advanced characteristics according to the needs of the projects. This object-oriented mechanism facilitates managing the varying parameters in REMix for multiple projects [30]. For the TIMES model, different front-end and back-end interfaces have been developed, of which VEDA is the most famous one [31]. To manage data in the TIMES model, VEDA-FE employs a tagging system in Microsoft Excel. By searching through worksheets, VEDA finds tags in a specific format describing parameters. Next, VEDA-FE compiles the scenario for the GAMS model to solve. Finally, after solving the model, the back-end module (i.e., VEDA-BE) collects output files to generate reports and plots. Although VEDA-FE/BE facilitates data management in TIMES, the data values should be manually inserted in tables. Manually entering data values can be a time-intensive task, particularly for medium to large-scale models. For example, a TIMES model containing 1200 processes and 181 commodities required more than 50 thousand data values across multiple worksheets [32]. As the size and complexity of a model increase, manual data entry becomes increasingly arduous and error-prone. Another shortcoming in VEDA-FE, which is addressed in the new VEDA2.0, is the lack of parallel processing. VEDA-FE requires the sequential reading and processing of input data, resulting in significantly increased processing time.

In the Long-Range Energy Alternatives Planning (LEAP) model, developers implemented a Graphical User Interface (GUI) that simplifies the process of developing new energy systems by removing the need for entering values directly into the databases [33]. Using an interface would help to minimize human errors. However, displaying the spatial dimension in LEAP requires additional components and is limited to a maximum resolution of 300×300 cells. Parzen et al. [34] propose utilizing available data in OpenStreetMap to improve the spatial dimension of an open-source Python-based energy system model called PyPSA-Earth; however, the model uses a command-line tool, specifically snake-make, for the workflow management, which can present a challenging learning curve for users with no prior programming knowledge. The Open-Source energy MOdeling SYStem (OSeMOSYS) is also another umbrella of optimization models with flexible time slices that rely on Python scripts and command-line interfaces for the workflow management system [35,36].

Energy system models can be confined to a shorter time horizon instead of decades (e.g., a single year) or one sector (e.g., the power sector) or limited to a specific region, thereby enabling modelers to improve the spatial resolution to a single home or a neighborhood. These confined models often tackle energy systems from a different angle to address technical questions. Alhamwi et al. [37] developed a Geographic Information System (GIS)-based ESOM called FlexGIS to optimize storage and flexibility technologies in urban areas by solving scenarios using the oemof.solph model. It incorporates spatial and temporal approaches and uses open-source data, primarily from OpenStreetMap, to export results in various formats or visualize them directly with desktop GIS software tools. However, there are other energy system models with different features and capabilities that use spatial data and provide a graphical interface to manage input and output data. For example,

HOMER is a software tool that simulates energy scenarios at the building, community, or microgrid scale and includes tables, graphs, and spatial analysis and visualization tools to analyze the results [38,39]. HOMER provides a graphical interface for specifying input data and has built-in GIS tools that allow users to import and view geospatial data such as building locations, energy infrastructure, and topography. The software also allows users to export simulation results into GIS formats for further analysis or visualization in external GIS software. Another ESOM, DER-CAM, optimizes distributed energy resource systems that incorporate different energy sources, storage options, and demand profiles using a Mixed-Integer Linear Program (MILP) model and a graphical interface [40–42]. DER-CAM does not have a built-in spatial visualization tool; however, the model provides detailed output data on the optimal deployment of distributed energy resources at different locations within a building or microgrid. These output data can be combined with external GIS software to create spatial visualizations. Similarly, EnergyPLAN provides an open-source energy system modeling approach that simulates how an entire region supplies and demands energy [43,44]. Although it does not have a built-in spatial visualization tool, users can export the output data from EnergyPLAN and use external GIS software to create spatial visualizations. In summary, energy modeling tools that provide GIS-based visualization capabilities and functionality help users and stakeholders understand and visualize the data and structural relationships between relevant spatial and temporal information, such as buildings, neighborhoods, and energy infrastructure, as well as their semantic relationships.

The BioEnergy OPTimization (BENOPT) model employs a tagging system, similar to that of VEDA, to generate scenarios using MATLAB [45,46]. However, the BENOPT model lacks an interface to generate scenarios; thus, the numbers should be added directly into Excel worksheets. Therefore, in this study, we develop a state-of-the-art UI for the extended BioEnergy OPTimization (BENOPTex) model to demonstrate the spatial and temporal characteristics of the energy systems while providing storytelling tools for effective communication.

Table 1 summarizes prominent energy modeling tools with respect to the model characteristics and the capacity of their interface in data visualization and storytelling. When it comes to the complexity of their user interfaces, two other ESOMs stand out besides BENOPTex: MESSAGEix and LEAP. Although these models are known for their powerful capabilities in energy systems modeling, their GUIs are confined to plotting results, ignoring opportunities emerging from applying storytelling techniques.

The remainder of the paper is organized as follows. Section 2 defines the methodology and challenges. In Section 3, we discuss ideal properties for the next generation of UIs. Finally, Section 4 concludes.

Table 1. Comparing reviewed energy models (alphabetically sorted) concerning the model characteristics and associated interface. Dash lines mean that no information is found related to that specific dimension.

Model	Programming Technique	Back-End Language	Front-End Language	User Interface	Spatial Visualization	Integrated Information Dissemination	Storytelling
BENOPT	LP	GAMS	MATLAB	MATLAB	No	No	No
DER-CAM	MILP	GAMS	.NET	DER-CAM desk-top	No	Yes	No
EnergyPLAN	Simulation	Delphi/Pascal	Delphi/Pascal	EnergyPLAN	No	No	No
FlexGIS	Simulation/LP	oemof.solph	Python/Java	CL	Yes	No	No
HOMER	Simulation	-	-	-	Yes	-	No
LEAP	Heuristics	-	-	LEAP	Yes	-	No
MARKAL	LP	GAMS	-	CL	No	No	No
MESSAGE	MILP	GAMS	-	CL	No	No	No
MESSAGEix	MILP	GAMS	Python & R	CL & web-based	No	Yes	No
OSeMOSYS	LP	GNU	Python	CL	Yes	No	No
PyPSA	MILP/LP	Python	Python	CL	Yes	No	No
REMix	MILP	GAMS	Python	CL	No	No	No
ReSTEP	Simulation	PowerShell	-	CL	No	No	No

Table 1. Cont.

Model	Programming Technique	Back-End Language	Front-End Language	User Interface	Spatial Visualization	Integrated Information Dissemination	Storytelling
TIMES	LP	GAMS	VB	VEDA-FE/BE	No	No	No
TIMES	LP	GAMS	C#/PostgreSQL	VEDA2.0	No	Yes	No
BENOPTex	LP	GAMS	C#	BENOPTex	Yes	Yes	Yes

2. Methodology

To develop the GUI, we employ the rendering engine of Academic Presenter (AP) [47], which combines the potency of slide-based presentation software products with canvas-based to create stories. AP has been used previously to visualize a wide variety of problems, including the traveling salesman problem [48,49], global language networks [50], and MicroRNAs synteny-based analysis [51,52]. However, in this manuscript, we use not only the engine but also the interface to manage the spatial resolution using an infinite canvas, while the temporal resolution is presented via discrete snapshots as time frames.

This section describes the expedition to devising an exemplary GUI that can be connected to the chosen optimization model (i.e., BENOPTex). Readers should note that the development of the new GUI for BENOPTex by no means is complete, and it is an ongoing process.

2.1. Requirements for an Ideal UI of ESOMs

To design effective UIs for ESOMs, it is crucial to have a comprehensive understanding of how energy system models function. ESOMs are built upon the concept of transforming primary energy carriers (e.g., biomass and solar) through conversion technologies into secondary energy carriers (e.g., electricity and biodiesel), which are then consumed by demand services to fulfill the specific end-use requirements specified by top-down models. These demand service technologies can be diverse, ranging from simple household appliances to large industrial machines, and they consume energy in various forms such as electricity and gas. These conversion and demand service technologies compete to satisfy demands in the most cost-effective and environmentally friendly manner respecting technical and political constraints. Figure 1 exhibits the streamlined reference energy system in BENOPTex.

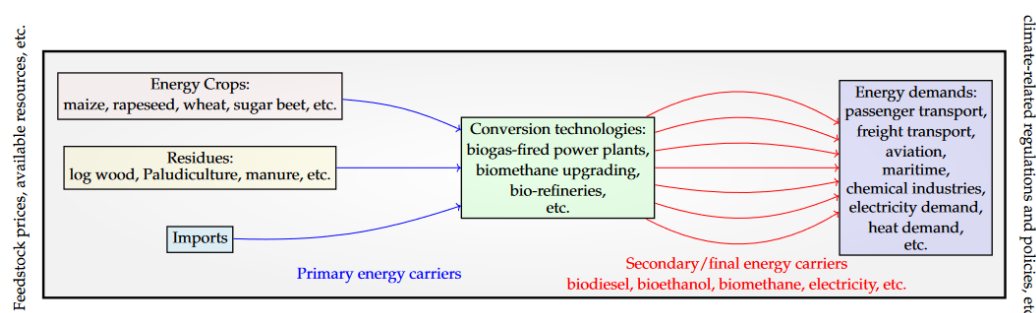


Figure 1. Schematic of BENOPTex inputs and outputs.

It is essential to recognize that the techno-economic parameters of commodities and technologies are highly dependent on factors such as deployment time and location; hence, these models should be able to visualize spatiotemporal aspects of various technologies to present a clear view for generating scenarios. It is vital to consider the spatial aspect of ESOMs in three dimensions, including depth, not just confined to the surface. Many technologies, such as geothermal or BioEnergy with Carbon Capture and Storage (BECCS), rely on underground resources for storage or energy extraction. Hence, the interface must consider the Z-axis. Additionally, the temporal aspect of ESOMs must be adequately distinguished by assigning flexible time resolutions to various technologies. For instance, while an hourly resolution for a biogas-fired power plant is reasonable, the availability of

biomass feedstock does not need to be modeled hourly. The model and interface must be able to distinguish the required temporal resolution for various technologies in order to save computation time and memory.

Overall, the UI of ESOMs should be designed to effectively visualize the spatiotemporal aspects of various technologies, considering three-dimensional space and assigning reasonable time resolutions to different technologies. By doing so, the interface can provide a clear view of possible scenarios and aid in decision-making processes. Figure 2 depicts the primary concept for an ideal front-end for ESOMs.

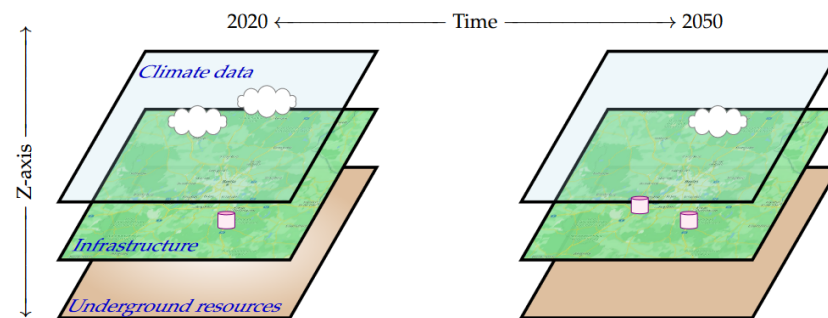


Figure 2. Schematic diagram of an ideal UI that takes into account the climate, land, and underground resources change over time. The pink cylinders represent energy infrastructures, such as biogas power plants.

2.2. The Visualizing Interface

To effectively visualize a complex multi-layer problem that evolves over time, a powerful rendering engine is essential. This engine should be capable of harnessing the immense computing power of modern graphics cards to accurately display the changing nature of the problem. In this section, we present a new approach for visualizing spatially resolved models using the state-of-the-art rendering engine of Academic Presenter (AP) [47]. The rendering engine of AP is implemented in C# using SlimDX [53], harnessing the power of a video graphics card without an intermediary.

The developed interface enables us to present the geographical information using an infinite canvas in multiple layers, while the morphing landscape through time is captured via snapshots of the system state. This feature assists users in visually identifying patterns, trends, and transformations over time, which subsequently helps them to draw an informed decision for generating scenarios. In fact, Chou et al. [54] investigate the effectiveness of various knowledge presentation methods (i.e., linear versus non-linear canvas) on learning performance. The authors conclude that canvas-based is a more efficient instructional medium for knowledge acquisition, while linear narratives demonstrated instructional effectiveness on long-term learning retention. These findings suggest that the choice of presentation method should be adjusted to the specific learning objectives and the audience's needs. For example, a canvas-based approach may be more appropriate for conveying complex information that requires immediate comprehension, while a linear narrative may be more effective for content that needs to be retained over time. A similar observation is reported by Chappin [55]. The author points out that using a whiteboard (or a canvas) can assist primary school students with no background knowledge about energy systems to develop a visual record of concepts.

Figure 3 displays the toolbox, ESOMs snapshots for temporal changes, and the canvas panels in the new BENOPTex interface. As shown in this figure, the central panel is where the infinite canvas is placed. This canvas reads and renders information from various GIS databases. The background of the canvas is directly connected to commercial mapping services (e.g., Bing Maps, Google Maps) using GMap.NET (the package can be accessed from the following address: <https://www.nuget.org/packages/GMap.NET> (accessed on 16 May 2023)) to update the view when zooming and panning. When the user modifies the view, the interface requests new blocks of information from the selected servers in

a multi-threaded manner. The selected mapping server sends the tiles for the requested regions to each thread separately. The thread managers in the interface then place each tile in its correct position asynchronously, thereby improving the refresh rate for rendering new scenes. For the sake of demonstration, two tiles are shown in Figure 3 for thread #1 and thread #2.

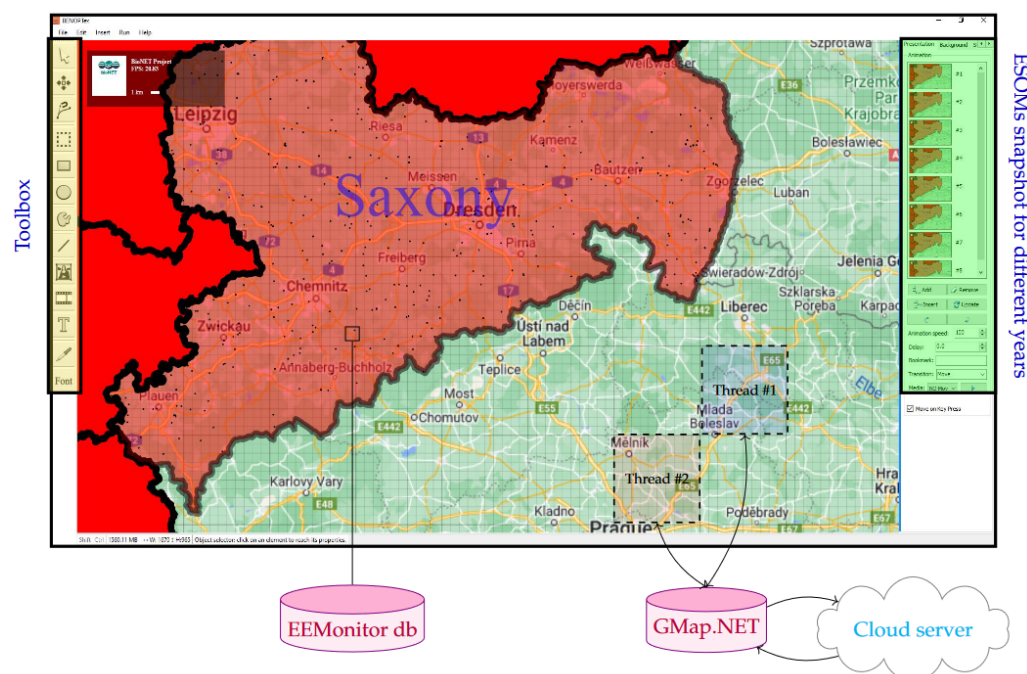


Figure 3. The infinite canvas is displayed in the central panel. The toolbox is highlighted in yellow. Users can insert images and videos or draw on the canvas to tell stories. The green box also shows the system snapshots that capture the system change through time.

With the comprehensive toolbox borrowed from AP's GUI, modelers can easily elevate energy systems visualizations into stories with a range of multimedia elements, including texts, equations, images, videos, and voiceovers. These features allow users to create engaging and informative stories that assist viewers in better understanding the underlying parameters in the model. In addition, the toolbox includes an annotation tool using a digitizer that enables modelers/presenters to highlight and emphasize key points in their stories, making it easier for audiences to follow along and stay engaged. According to anecdotal evidence from sources such as Roam [56] and Lee et al. [57], it is suggested that dynamic sketches accompanied by narration could be a more effective means of delivering information compared to conventional presentations. The annotation tool offers an editable layer-based drawing system that allows movements on the canvas to be replayed whenever needed. The toolbox provides users with a range of pens and highlighters that are easily accessible. Additionally, users have the ability to adjust the replay speed to suit their needs. In Figure 4, a digitizer is utilized to highlight a region in Saxony, where many agricultural lands are available with comparatively fewer biogas-fired power plants to use their residues. Using arrows, the modeler shows that this region is the centroid of the three most populated cities in Saxony, which can provide an opportunity to dispatch the generated electricity with low transmission loss. The annotation allows modelers and content creators to create engaging stories that can be presented to stakeholders, by which they can justify their results. On the left-hand side, the GUI displays various editing options when the annotation tool is selected.

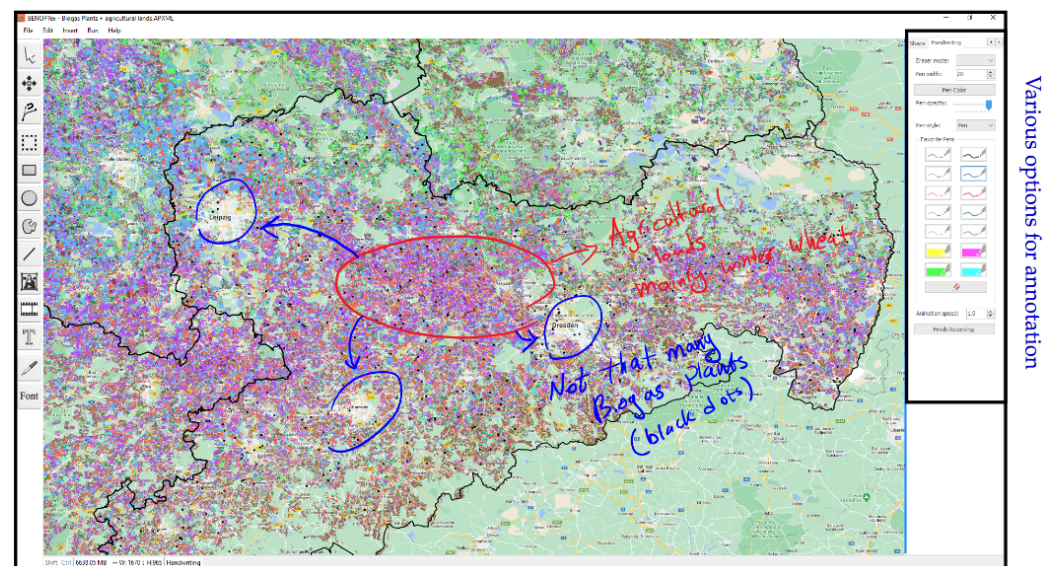


Figure 4. Using a digitizer to draw on the map. It displays that there are not enough biogas power plants located near agricultural lands and the three most populated cities in Saxony.

The GIS data related to available bioenergy and renewable energy facilities are acquired from the EE-Monitor project [58] and the Core Energy Market Data Register [59]. These renewable energy facilities can additionally be simulated in terms of their electricity production using the ReSTEP models, providing further important input information for ESOMs. To calculate the electricity generated from variable renewables, i.e., wind turbines and PV systems, spatially and temporally resolved weather data are required in addition to the necessary plant data containing geographical locations and technical parameters of the selected renewable energy facilities. In this way, future climate change effects can also be included in the numerical simulations, which will further improve the prediction results of the ESOM scenarios [60]. The electricity production data generated by ReSTEP are time series with a maximum spatial resolution at the plant site level and a temporal resolution based on the weather or climate data used, typically one hour. Thus, time series with any required spatiotemporal resolution equal to or lower than these maximum resolutions can be provided as input information for the subsequent ESOMs. Figure 5 shows the scheme for generating electricity production data from variable renewables using the ReSTEP models with the necessary plant and weather data.

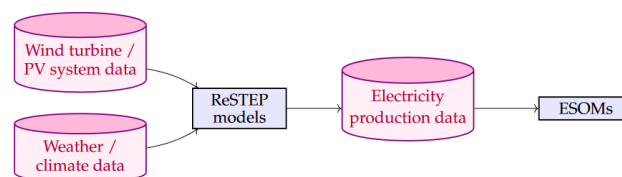


Figure 5. Scheme for generating electricity production data of renewable energy facilities by ReSTEP required as input information for ESOMs.

The data have been cleaned and converted into a proper GIS format. To accelerate the visualization process, the UI checks the size of facilities with respect to the zoom factor and the visible region. If we are on a national level, the interface ignores drawing these facilities. Similarly, we are planning to connect the new BENOPTex visualizer to new GIS datasets for the land use [61] and forest types [62].

By utilizing the described interface, users can easily generate scenarios by visually adjusting parameters in BENOPTex. Once created, these scenarios are sent to the GAMS solver for optimization of decision variables. Finally, the optimal values of the decision variables will be read from the GDX file.

2.3. Information Dissemination

The GUI has been carefully designed to seamlessly integrate BENOPTex's visualization and information dissemination processes. This means that users can conveniently and efficiently create, manipulate, and share visualizations of their inputs and outputs. The visualizer's view can be exported to a wide variety of static and dynamic media formats, including a web-friendly code that can be easily embedded into projects' web pages. Using HTML5 and CSS3 [63] technologies, an online platform is created that accepts uploaded project files (please visit <https://APresenter.com> (accessed on 16 May 2023)). This platform will allow modelers to present stories, scenarios, and results of ESOMs using web browsers. This ensures that users can easily share their insights with stakeholders, regardless of the utilized platform or device type.

To transfer the model results/data to the server, the front-end interface first reads inputs and parameters. Then, all visual clues are translated into an extensible markup language (XML) file, in which elements (e.g., images, voices, handwriting) are encoded and embedded. Next, the visualizer assigns a unique identification number to the XML file and uploads it to the server using the hypertext transfer protocol after verifying the user's credentials. Using the same identification number, the stored projects on the server can be invoked and shared with audiences. Figure 6 depicts the information flow and sequence of processes (i.e., data curation, scenario generation, optimization, and information dissemination).

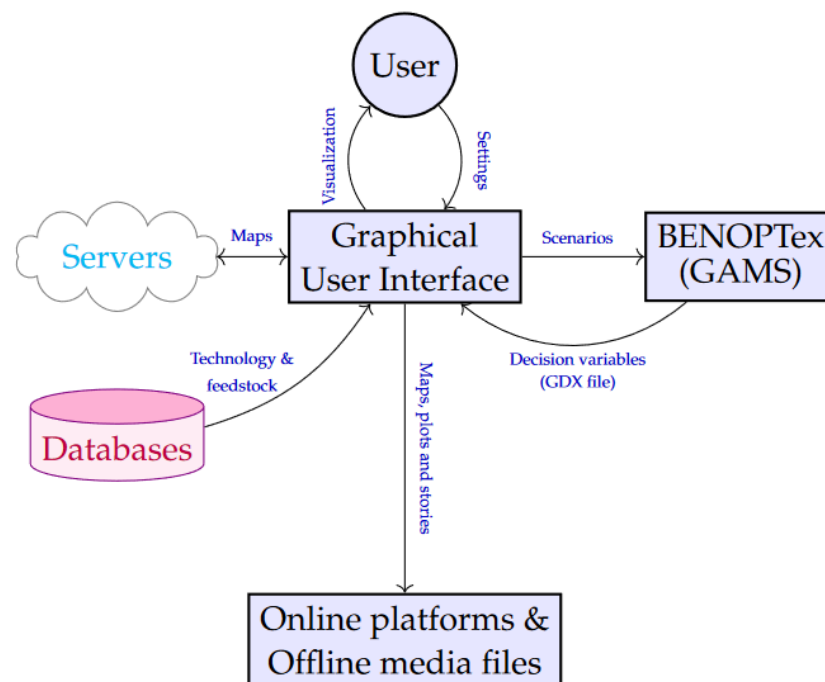


Figure 6. The flow of information from databases to the solver and the online and offline visualizer.

3. Discussion

Energy system models are often by-products of research projects carried out by universities and research centers facing tight budgets and time constraints. Hence, researchers have to prioritize their tasks to ensure the full development of the main component of these models, which can sometimes deprioritize the development of user-friendly interfaces. To aggravate the situation, visualizers and UIs can often be developed after the completion of the main model, which can mislead researchers to undervalue their importance. As a result, many models remain in their primitive script forms to answer specific questions, limiting their applicability and maintainability.

To extend the use of these models beyond the scope of their parent projects, a community of users is required, emphasizing the critical importance of intuitive and accessible

interfaces. One possible strategy is to develop multiple versions of the model tailored to specific purposes. For example, LPJ-GUESS (a dynamic global vegetation model) has two distinct versions—one for research and another for educational purposes [64]. The educational variant of LPJ-GUESS offers a GUI and simpler instructions, making it more user-friendly for beginners. Nonetheless, managing version control of these customized models may pose a challenge, as changes made to one version may not be compatible with the other.

In this manuscript, the key aspects of ESOMs have been comprehensively reviewed, which aids in identifying the optimal design for a UI that satisfies users' needs. The thought process has been described in detail, exposing the technical difficulties that need to be addressed. It is anticipated that the next generation of ESOMs will be GIS-based, and therefore, spatial detail should be integrated into future UIs. This can be achieved either by linking scripts to available GIS tools, such as QGIS and ArcGIS, or by creating an entirely new GUI that meets the ESOMs' requirements.

Moreover, the temporal resolution of such models should be adjustable to suit the requirements of technologies and objectives. This will minimize the runtime of optimization models. Finally, it is expected to see more hybrid models in the future as policymakers aim to gain a comprehensive understanding of the problem by incorporating the viewpoints of heterogeneous stakeholders. As a result, future UIs should be devised to consolidate the understanding of these stakeholders using visualization and storytelling techniques. Furthermore, the latest UIs should enable convenient interactions with other optimization/simulation models. A sophisticated GUI can be created apart from the optimization model, much like the GAMS software, in which the model only needs to be written once, and the solver can be specified afterward based on the model's characteristics [65].

By analyzing various ESOMs, this study shows that the GUI is the Achilles' heel of these models. Unfortunately, the status quo is lagging behind the other aspects of these energy modeling tools. Therefore, project managers and developers should dedicate enough resources to enhance the user-friendliness of these interfaces. A glimpse of the future generation of UIs can suggest that these interfaces will be streamlined using large language models, such as the Generative Pre-trained Transformer (GPT) [66]. The Artificial Intelligence (AI) will enable users to generate scenarios and modify the optimization code based on descriptions and given datasets.

4. Conclusions

This study reiterates the importance of employing data visualization and storytelling techniques to better align stakeholders' understandings of energy systems and refine their expectations. Unfortunately, many models suffer from poor UI with technical complexities that make them impractical to outsiders. This shortcoming prevents the community from forming around these ESOMs; however, expectations are growing rapidly in favor of developing user-friendly software tools for efficient data management with minimum space for human errors. Therefore, in this manuscript, major dimensions are first identified for an ideal user interface, by which one can address future requests from these optimization models. Next, a GUI has been developed for the selected ESOM (i.e., BENOPTex) that visualizes various datasets and generates stories around them.

This manuscript can be extended in multiple directions. Linking power market models (e.g., EMSimulator [67] and AMIRIS [68]), climate models (e.g., REMO [69,70]), or vegetation models (e.g., FORMIND [71]) can be followed with the selected ESOMs using an advanced user interface. Moreover, the impact of data visualization and storytelling in the developed GUI on stakeholders' collaboration can be investigated. Finally, it is crucial to devise and implement high-performance optimization techniques for efficiently solving spatially detailed ESOMs.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	artificial intelligence
AP	academic presenter
BECCS	bioenergy with carbon capture and storage
BENOPTex	extended bioenergy optimization model
ESOMs	energy system optimization models
GPT	generative pre-trained transformer
GUI	graphical user interface
IEA	international energy agency
MESSAGE	model for energy supply strategy alternatives and their general environmental impact
OSeMOSYS	open-source energy modeling system
PSMs	power sector models
REMix	renewable energy mix
ReSTEP	renewable spatial-temporal electricity production
VRE	variable renewable energies
UI	user interface
XML	extensible markup language

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