An educational tool to optimize the consumption of primary energy in thermal-based distributed energy systems

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Abstract: The use of highly energy-efficient technologies is an important tool to tackle today's energy and environmental challenges. The importance of these technologies creates a need to focus on the development of energy courses as part of the engineering curriculum. In such energy-related courses, user-friendly applications such as MS Excel can be used to enhance educational goals like the assessment of the energy consumption of these energy-efficient technologies. This research paper presents the MS Excel-based tool developed to minimize the consumption of fossil fuel-based primary energy of a Distributed Energy (DE) system, which includes base Combined Heat and Power (CHP), Thermal Energy Storage (TES), and a boiler. Moreover, an educational component comprises the utilization of a MS Excel tool to help students estimate the system's minimum primary energy consumption. Results show that the combined use of base CHP and TES in a DE system can lead to a considerable decrease in primary energy consumption. The accessibility and familiarity of many students and companies with MS Excel can be an impactful educational tool for assessing the development of DE systems.

Introduction and Background

The use of highly energy-efficient technologies is an important tool to tackle today's energy and environmental challenges. The importance of these technologies creates a need to focus on the development of energy courses as part of the engineering curriculum. Engineering learning methods and technology are constantly evolving [1] but the industry is still using traditional methods such as MS Office due to its widespread use, easiness, and low cost [2], [3], [4]. Therefore, in energy-related courses, an educational tool based on applications such as MS Excel is useful in the transitional period between pen and paper and more advanced and costly software applications. Moreover, accessible applications can be used to enhance educational goals like the assessment of the energy consumption of these energy-efficient technologies.

To address the use of accessible applications in the learning of energy-efficient technologies, this paper describes a Combined Heat and Power (CHP) based Distributed Energy (DE) system deployed to increase energy efficiency. When properly designed, a DE system can minimize primary energy use, decrease greenhouse gas emissions, and improve the resiliency of the electrical energy supply. The method is based on a developed optimization technique used to minimize the consumption of fossil fuel-based primary energy of a DE system, which includes base CHP, Thermal Energy Storage (TES), boiler, and electricity from the grid when necessary [5].

There are tools in the market that can make similar assessments as the developed tool, therefore it is important to understand these available tools and the reason why a new tool is developed. Several tools have been developed to evaluate the feasibility of CHP [6], [7]. Moreover, tools also have been developed to choose the optimal combination of technologies of DE systems [8], [9]. Some of these tools are freely accessible [6], [7] while others are proprietary software only commercially available [8], [9]. These different tools are distinguished for using simulation and

optimization methods, being that optimization tools focus on technology and/or economic factors. Table 1 presents the characteristics of these DE systems assessment tools.

Table 1- DE systems assessment tools

TOOL	AVAILABILITY	LEARNING/INPUT TIME	CHP	MICROGRIDS	TES
BCHP	Free	Lengthy	Yes	No	No
RETSCREEN	Free	Lengthy	Yes	Yes	No
HOMER	Commercial	Reasonable	Yes	Yes	No
DER-CAM	Commercial	Lengthy	Yes	Yes	Yes

Table 1 shows that from the tools available, only the DER-CAM can address all the components of the proposed system. The main goal of DER-CAM is the microgrid economic prioritization [10]. A reported limitation of DER-CAM is the use of sensible heat storage (water) for TES modeling [11]. In terms of usability, users need to insert an extensive set of key inputs leading to the task becoming tedious. Also, as the tool has its own software development, users can expect a substantial learning curve. Moreover, to use DER-CAM a paid license is required which can be an obstacle for educational institutions to use it. A common limitation of all the tools is that they either lack or limit the thermal storage, which is an important component of the tool presented in this paper. Moreover, the tools are either difficult to learn or present tedious tasks for data input and can be expensive to acquire. Therefore, considering educational settings, this paper presents a MS Excel-based optimization tool with the capacity of simple data import.

The tool presented in this paper can be used as a module of a 3-credit course, such as Energy Storage [12], Combined Heat and Power [13], or Distributed Energy Systems [14]. Moreover, the tool can be used as part of a project which can be used for the course assessment.

Method

System design. The system used in this paper is a CHP-based DE system to supply the thermal demand (q_D) and the electrical demand (e_D) to the campus. The theoretical design system is based on several technologies, such as CHP with TES, additional thermal energy provided by an on-site boiler and additional electricity provided from the central electric grid. The system detailed in Figure 1 is composed of a site-based CHP gas combustion turbine that can supply both thermal (q_{CHP}) and electrical (e_{CHP}) energy; a site TES system - also known as a steam accumulator - that receives thermal energy from the CHP system (q_{CHP_TES}) and can supply the thermal demand (q_{TES_D}); an industrial boiler at the site that can supply additional site thermal energy (q_B); and an off-site electrical power plant that can supply electrical energy (e_{PP}) via the central grid transmission and distribution (GTD) system.
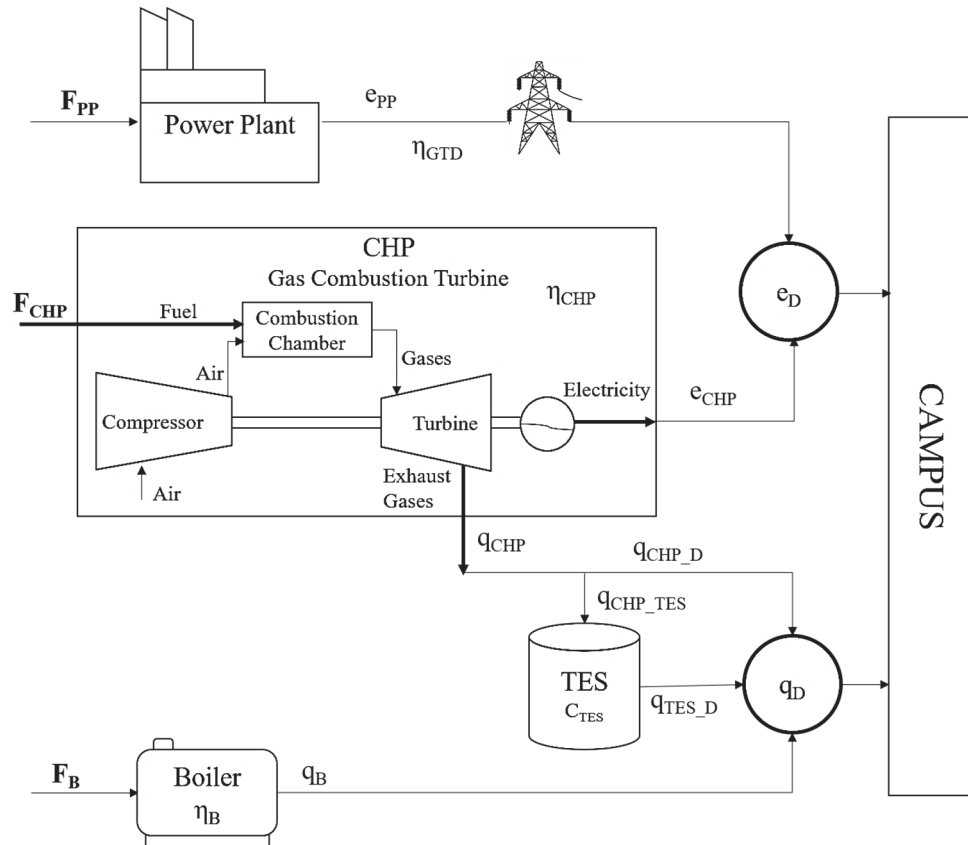
Figure 1 – CHP-based DE system design

Input data. The input data used is the University Campus thermal and electrical data for the full year of 2015 [5]. The campus is located in a humid continental climate zone [15], which is characterized by significant differences in seasonal temperature, with warm to hot humid summers and cold winters. The input thermal and electrical data represent hourly values, and all these data values were converted to MW for consistency of comparison. Figure 2 provides an overview of the overall thermal demand for every hour during the year and Figure 3 shows the overall electrical demand. The first hour in both figures represents, respectively, the thermal and electrical demand for the first hour of the year. Figure 2 thus shows that the thermal demand is substantially higher during the Winter season than during the Summer due to the heating loads. This pattern is reversed for the electrical demand in Figure 3 due to the cooling loads.
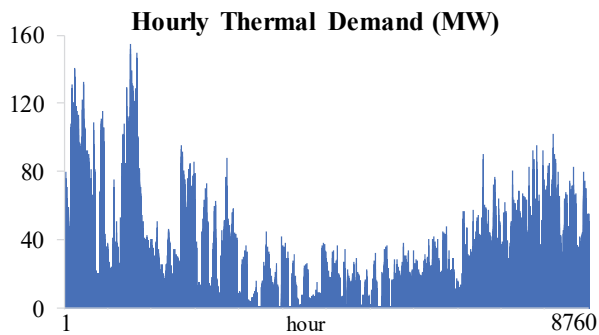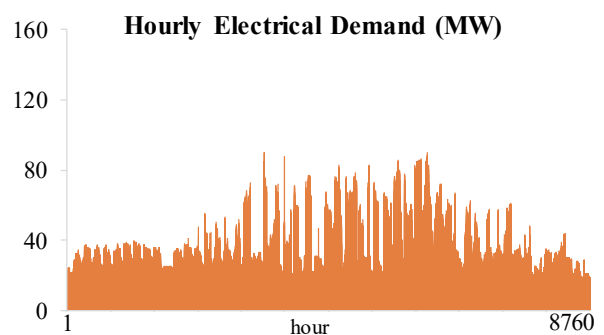

Figure 2 - Campus hourly thermal demand, MW

Figure 3 – Campus hourly electrical demand, MW

Table 2 below shows other important input values. These values represent the efficiency of the energy generation equipment, being η_{CHP} the efficiency of the CHP system, λ_{CHP} the thermal-to-electric ratio, η_B the efficiency of the boiler, η_{GTD} the efficiency of the power plant, which includes generation, transmission, and distribution. The values on the table are constant throughout the assessment. Nonetheless, these values can be modified for other assessments.

Table 2 - Input values for energy generation equipment.

EQUIPMENT	MEASURE	VALUE	
CHP	η_{CHP}	42%	
	λ_{CHP}	1.5	
BOILER	η_B	80%	
POWER PLANT	η_{GTD}	33%	
STEAM STORAGE	Capacity	63.63	MWh

MS Excel tool. This tool was developed based on an optimization study on which the goal was to find the minimum overall fossil fuel consumption for the system composed of CHP equipment, TES, boiler, and the central electrical power plant presented in the previous section [5]. The mathematical optimization was developed using the MS Excel solver with a Generalized Reduced Gradient (GRG) non-linear technique or a constrained nonlinear optimization. Some studies used other methods such as MILP, but the objective is to facilitate the process using an accessible and widely used software such as MS Excel [16] with a thermal demand-driven CHP configuration focus [5].

The GRG method consists of analyzing how the gradient of the objective function changes with changes in the decision variables and, when the partial derivatives equal zero, assumes that the optimal solution is achieved [17]. This method is fast compared with other nonlinear methods. Nonetheless, GRG typically can only find a locally optimal solution to a nonlinear, non-convex problem. In optimization, an optimal local solution is the best solution found while searching for a neighboring solution set. On the other hand, a globally optimal solution is the best solution found considering every possible solution. So, when using the GRG method, several initial conditions should be tested to determine the best optimal solution, which might be a local optimum instead of the global optimum. Moreover, the function needs to be continuous because if the function is discrete, the solver will likely not achieve an optimal solution [18]. In [5], a sensitivity analysis is presented, where multiple initial conditions are tested to ensure that the best optimal solution is achieved.

The tool presents several tabs, some are informative only, while others need some user input. The main three tabs are the diagram of the system, the data tab, and the assessment tab:
1) The diagram of the system presented in Figure 4 is based on the theoretical design system described in the previous section.
2) The data tab presented in Figure 5 is where the user can insert hourly data for thermal energy, in klb of steam, and electricity, in kW. The tool will convert the inserted values into MW.
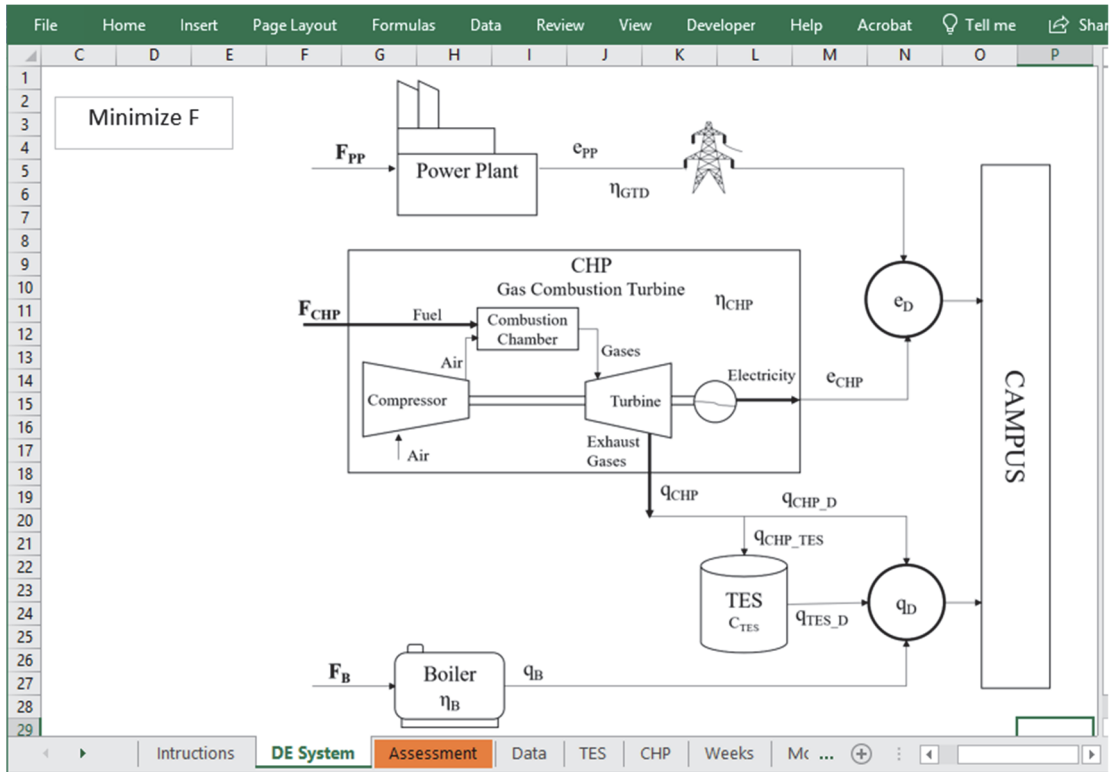
Figure 4 – CHP-based DE system design included in the tool

Figure 5 – Data input tab for the CHP-based DE system optimization tool

3) The assessment tab presented in Figure 6 shows the data to be chosen – cells highlighted in blue - as well as the output of the assessment. The process to assess the minimum primary energy is the following:
   a. The "Insert data" cell will lead to the data tab presented in Figure 5;
   b. To choose the CHP system, a drop-down menu allows the user to choose between five systems with specified values on the table depicted on the right side. The variables chosen are the thermal efficiency of the CHP system ($\eta_{Thermal\_CHP}$), the thermal-to-electric ratio of the system (λ_{CHP}), and the steam output of the CHP gas turbine system in MW;
   c. The boiler needs an efficiency input (η_B);
   d. The electricity from the grid needs the generation, transmission, and distribution efficiency (η_{GTD});
   e. The TES needs the input for the steam pressure that can be created by the CHP system (Pressure), the pressure needed to supply the site thermal demand (Design pressure), and the dimensions (length and diameter) of the storage tank;
   f. The user needs to choose a period of time during which the CHP energy production is fixed, by year, season, month, or week. Clicking in this drop-down menu and choosing a period will make the optimization run;
   g. When the calculation is over, the output cells present the results as the minimum overall primary energy, the minimum primary energy allocated to the thermal energy, and the minimum primary energy allocated to the electrical energy.
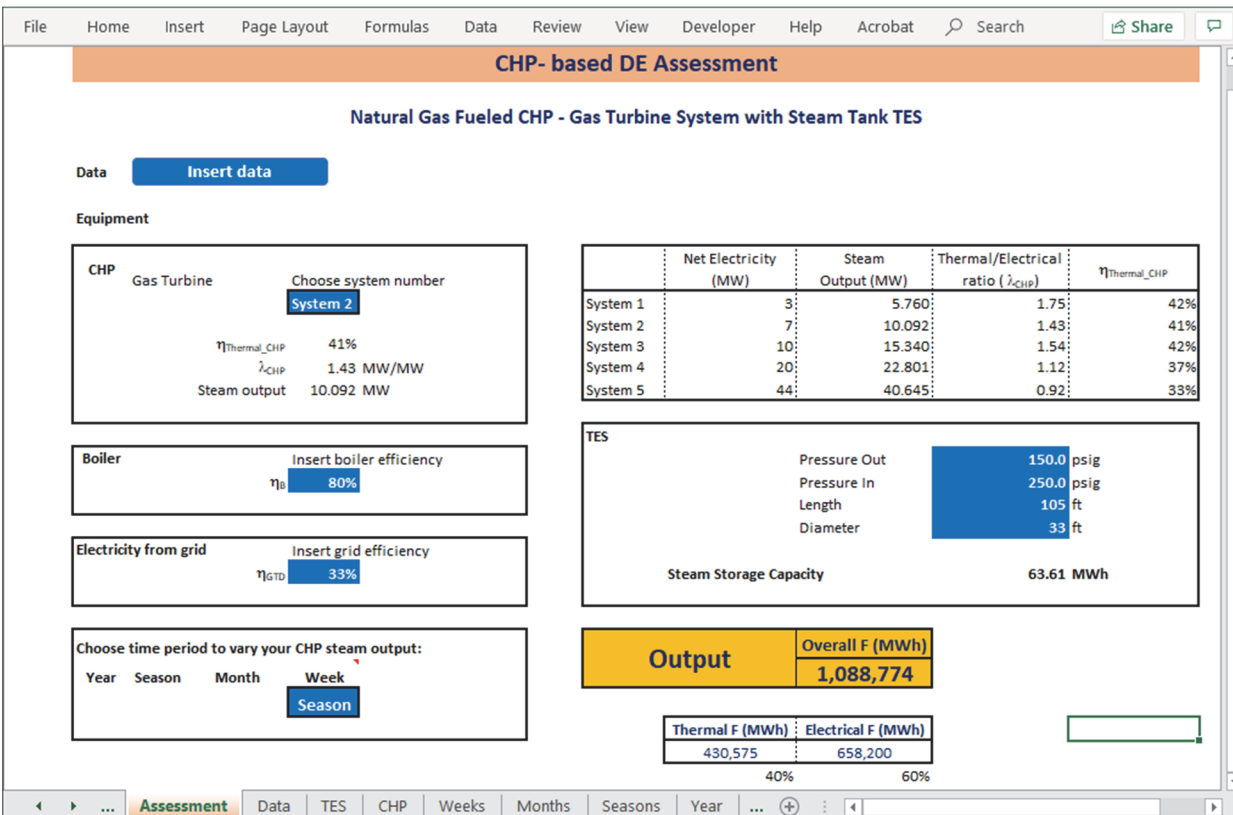

Figure 6 – Assessment tab for the CHP-based DE system optimization tool

Results

Optimization output. For this optimization, constraints need to be formulated to represent the limitations of the system. The results presented in Figure 7 represent a scenario with two constraints. The first constraint where TES has a maximum value of 63 MW, and the second constraint where the CHP system is turned off when the thermal demand is below 5.76 MW. It assumes that the amount of CHP thermal energy produced is fixed during certain time periods, as it is not feasible to change the amount of CHP produced every hour. Four different cases are considered during which the CHP production is fixed: 1 year, 4 seasons, 12 months, 53 weeks. This means the CHP thermal energy produced is: a) the same for one full year, b) it is fixed during each season, only changing four times in one year, c) it is fixed during each month, changing 12 times in one year, and d) it is fixed during each week, changing 53 times in one year.
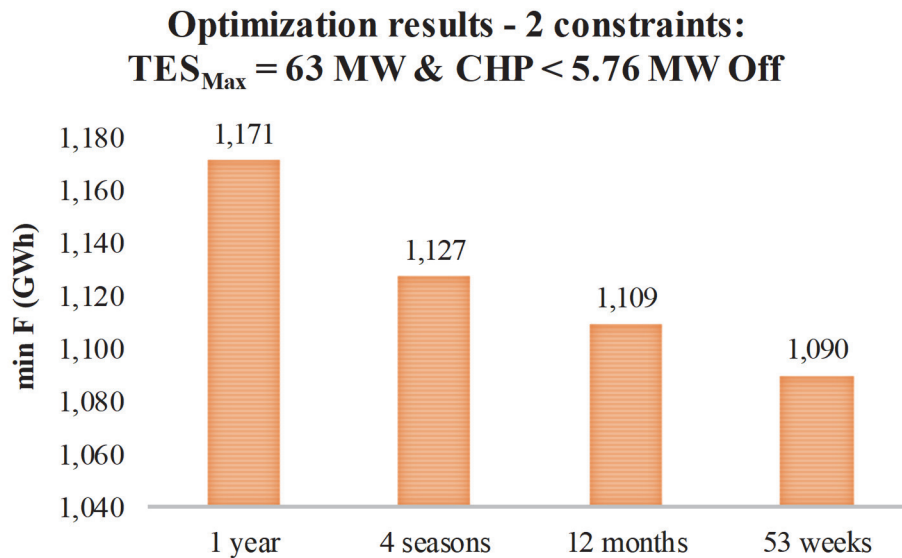
Figure 7 – Optimization scenario with 2 constraints:
Maximum TES = 63 MW and CHP < 5.76 MW is Off, for CHP output fixed time periods

Reasonableness assessment. To assess the reasonableness of the results a primary energy dataset was used. For the same campus, the primary energy consumed for the same year 2015 was 1,206 GWh, which included 515 GWh of fossil fuels and an electricity primary energy consumption equivalent of 690 GWh. Figure 8 shows that when the CHP system produces the same amount of energy for each hour of the year, it results in a 3% decrease in primary energy consumption compared to this real case. The decreases are even more substantial for the 4 seasons case (7%), the 12 months case (9%), and the 53 weeks case (11%). This shows that the proposed method can consistently lead to lower primary energy consumption than the method used in practice.

**Reasonableness assessment:
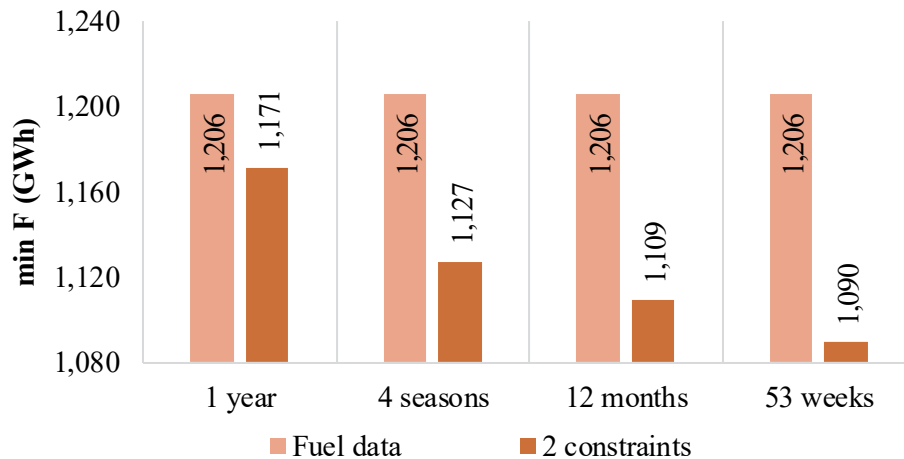optimization results vs. primary energy dataset**

Figure 8 – Reasonableness assessment of the results of the optimization scenario with 2 constraints: Maximum TES = 63 MW and CHP < 5.76 MW is Off, for CHP output fixed time periods, using a primary energy dataset

Discussion

This paper presents an easily-accessible MS Excel tool that can optimize the selection of previously described energy systems to minimize primary energy. This tool is developed to be used as a module of a 3-credit energy course or as part of a project which can be used for course assessment. The instructor can develop a project based on the proposed design. To use this tool as is, the students need to be familiar with MS Excel but not proficient. The students will need to use basic functions such as insert data in cells, choose from drop-down menus, and click buttons, as explained next. First, students will need to insert the hourly thermal and electrical data demand. Second, the students can vary the input variables embedded in the tool, such as, the CHP system used, adjust the efficiency of the boiler, the efficiency of the electrical system, and the capacity of the TES. Finally, the students can choose the period time to vary the CHP steam output and run the tool resulting in the optimized value. The tool will assess the minimum amount of natural gas that the chosen equipment will need for the inserted data. After using this tool, the students will learn what variables are used and its importance, the sensitivity of the model, and overall, they will assess how much energy can be saved under the chosen conditions.

The advantages of the developed tool are that it is convenient, robust, and widely available for students. First, the convenience is shown by being user-friendly, presenting clear input fields for data and equipment, allowing users to explore different scenarios and equipment setups quickly, and providing clear directions on potential energy savings when testing out different equipment setups. Second, despite not using a complicated algorithm, results are robust as confirmed by testing a variety of starting values leading to similar results most of the time. Third, educational settings, such as higher education institutions, have easy access to MS Excel due to its widespread use, easiness, and low cost, so the tool can be easily accessed by students at all institutions.

Future work

Nonetheless, the tool has yet to be tested in the classroom. Therefore, suggestions for future work include pilot testing in an energy-based engineering course to validate the tool in a classroom setting. For this validation, students' surveys and assessments are suggested, as well as instructor feedback. The student survey can present questions such as ease of use, comprehension level, and learning outcomes. The instructor's feedback can incorporate suggestions for improvement based on classroom observations and assessment outcomes. Based on the results of this educational validation, adjustments to the tool can be made.

On the other hand, to validate the technical component of the tool, an idea for future development is to change the components or the settings of the system, as the tool currently uses a set of pre-established configurations. For example, increase the complexity of the system by adding electrical storage to the tool, or program the tool to obtain an outcome of the CO_2 emissions or total cost. Nonetheless, the students need to have a more advance understanding of MS Excel to make these changes. These changes can be part of the classroom component in which students can explore different settings and scenarios, according to their chosen system configuration. Another suggestion for future validation, as the method used a single set of data, is to use other data sets of other campus facilities with similar characteristics.

Conclusions

In days where energy technology is developed at an incredible pace, the need to create knowledgeable and adaptable professionals can have a great impact on the future of this World. The role of Higher Education, and specifically Engineering, has a huge impact on the development of the referred professionals. However, the methods used in the classroom are often difficult to access and use, and students spend more time learning new software than learning the course objectives. The MS Excel-based tool presented in this paper, due to its accessibility and relatively short learning curve, can help students to learn how to do energy assessments by focusing on the content of the course. Access to this tool can be requested by contacting Joana Marques Melo to the following email optimizpe.mmelo@gmail.com.

References

[1] V. Jones and J. H. Jo, "Ubiquitous learning environment: An adaptive teaching system using ubiquitous technology," in *Beyond the comfort zone: Proceedings of the 21st ASCILITE Conference*, 2004, vol. 468, p. 474, [Online]. Available: https://www.ascilite.org/conferences/perth04/procs/jones.html.

[2] T. L. Garwood, B. R. Hughes, M. R. Oates, D. O'connor, and R. Hughes, "A review of energy simulation tools for the manufacturing sector," *Renewable and Sustainable Energy Reviews*, vol. 81, no. P1, pp. 895–911, 2018, doi: 10.1016/j.rser.2017.08.063.

[3] M. Niazkar and S. H. Afzali, "Application of Excel spreadsheet in engineering education," in *Proc. of the First International & Fourth National Conference on Engineering Education*, 2015, pp. 10–12.

[4] S. Navaee, "Utilization of EXCEL in solving structural analysis problems," in *ASEE Annual Conference Proceedings*, 2003, pp. 12629–12641.

[5] J. Marques Melo, "Optimization of Combined Heat and Power based Distributed Energy Systems with Thermal Storage to decrease Primary Energy consumption," Ph. D. Dissertation, Pennsylvania State University, University Park, PA, USA, 2019.

[6] *BCHP Screening Tool*. US Department of Energy: ORNL, 2007.

[7] *RETScreen*. Natural Resources Canada, 2010.

[8] *HOMER (Hybrid Optimization of Multiple Energy Resources)*. HOMER Energy LLC, 2014.

[9] *DER-CAM (Distributed Energy Resources -Customer Adoption Model)*. Lawrence Berkeley National Laboratory, 2016

[10] Lawrence Berkeley National Laboratory, "DER-CAM User Manual," Lawrence Berkeley National Laboratory (LBNL), Berkeley, California, USA, Manual, 2016. Accessed: Apr. 12, 2018. [Online]. Available: https://building-microgrid.lbl.gov/sites/default/files/DER-CAM_User_Manual_V4-414_0.pdf.

[11] D. Steen, M. Stadler, G. Cardoso, M. Groissböck, N. DeForest, and C. Marnay, "Modeling of thermal storage systems in MILP distributed energy resource models," *Applied Energy*, vol. 137, pp. 782–792, Jan. 2015, doi: 10.1016/j.apenergy.2014.07.036.

[12] NTNU, "TFNE3008: Energy storage," 2019. [Online]. Available: https://www.ntnu.edu/studies/courses/TFNE3008#tab=omEmnet. [Accessed: 27-Jan-2020].

[13] Penn State University, "AE 551: Combined Heat and Power System Design for Buildings," 2019. [Online]. Available: https://bulletins.psu.edu/search/?scontext=courses&search=ae+551. [Accessed: 27-Jan-2020].

[14] NTNU, "ENE3004: Electrical energy systems and district heating," 2019. [Online]. Available: https://www.ntnu.edu/studies/courses/ENE3004#tab=omEmnet. [Accessed: 27-Jan-2020].

[15] M. C. Peel, B. L. Finlayson, and T. A. McMahon, "Updated world map of the Köppen-Geiger climate classification," *Hydrology and Earth System Sciences*, vol. 11, no. 5, pp. 1633–1644, Oct. 2007.

[16] Z. Bogdan, M. Baburic, and N. Serman, "Optimization model for EL-TO Zagreb cogeneration plant," in *Proceedings of the 23rd International Conference on Information Technology Interfaces, 2001. ITI 2001.*, 2001, pp. 287--295 vol.1, doi: 10.1109/ITI.2001.938032.

[17] L. S. Lasdon, A. D. Waren, A. Jain, and M. Ratner, "Design and Testing of a Generalized Reduced Gradient Code for Nonlinear Programming," *ACM Trans. Math. Softw.*, vol. 4, no. 1, pp. 34–50, Mar. 1978, doi: 10.1145/355769.355773.

[18] D. C. Yu, J. E. Fagan, B. Foote, and A. A. Aly, "An optimal load flow study by the generalized reduced gradient approach," *Electric Power Systems Research*, vol. 10, no. 1, pp. 47–53, Jan. 1986, doi: 10.1016/0378-7796(86)90048-9.