Alternative Energy Design Toolkit

by

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Abstract

This thesis concerns the concepts, structure, and applications of the Alternative Energy Design Toolkit. The toolkit is aimed to provide a widely accessible, easy to use, flexible, yet powerful modeling environment for assisting design associated with renewable energy technologies. Exchanges of ideas and knowledge among the users are also highly encouraged and facilitated.

The toolkit is composed of three important components: a collection of models that are fundamentals of renewable energy design, a modeling environment called DOME, which is used as the toolkit's enabler, and a supporting Web site.

At the beginning, a comprehensive survey of existing tools for renewable energy design is presented. Then, the detailed descriptions and key capabilities of the toolkit's components are provided. In addition, a collection of solar energy models, which is the initial set of models in the toolkit, is also presented.

The toolkit is utilized in two design scenarios: a design of a stand-alone PV system, and a trade-off analysis of a hybrid PV-diesel electricity system. In both design scenarios, the models in the toolkit are proven to be useful and convenient resources. The processes of making the representations of the systems are straight-forward, and the analysis mechanisms that the toolkit provides make the design process simple yet effective.

Thesis Supervisor: David Wallace
Title: Esther and Harold E. Edgerton Associate Professor

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Introduction

1.1 Motivation

The foreseeable depletion of the world's oil and gas reserves is a growing concern for the global economy, and the effects of the greenhouse phenomenon and the pollution emitted from carbon-based fuels have critical environmental implications. These issues have led to a search for renewable and cleaner sources of energy, such as solar, wind, and tidal. Some developed countries have already studied and started implementing technologies to harvest these alternative energy sources. Still, most countries, especially the developing ones, are far behind in the process but nevertheless eagerly trying to catch up.

In a developing country, renewable energies mean more than just clean, alternative energy sources. They can provide a quicker path to development of the country and a better standard of living of its people. Electrification in rural areas that are unreachable by a grid can be made possible and affordable. Improvements in standards of education, communication, and health-care typically then follow the availability of reliable power. Moreover, the use of alternative energy sources can help alleviate severe pollution problems in developing countries that result from dirty energy sources.

This dire need is the foundation of the author's interest in the area of renewable energies. However, the successful implementation of renewable energy systems is a challenge, especially for developing countries. The renewable energy systems require intensive and careful design that typically involves iterative, expensive, and time-consuming pilot programs. Since most renewable energies are geographically dependent, studies to identify possible energy sources for one particular location are required. Furthermore, to achieve a highly efficient, yet economically feasible system, a hybrid system of multiple renewable energy sources might need to be considered. Thus, the complexity and research cost associated with large-scale renewable energy is a major impediment to the advancement of renewable energy plans in developing countries. The interest of this thesis is to find better methods for designing integrated renewable energy systems.

1.2 Overview

This thesis concerns the concepts, structure, and applications of the Alternative Energy Design Toolkit. The toolkit is aimed to provide a widely accessible, easy to use, flexible, yet powerful modeling environment for assisting design that associates with renewable energy technologies.

Chapter 2 provides a survey of related work. In the survey, a number of computer-based tools that associate with renewable energy design are discussed. The tools are categorized by the range of renewable technologies that they incorporate. In addition, there are a surprisingly high number of tools that are developed explicitly for building applications. These tools are presented and discussed in a separate subsection. The following section provides observations made from the key characteristics and capabilities of the tools in the survey. Then, following the observations, all important attributes that should be possessed in an effective renewable energy design tool are identified.

Chapter 3 provides detail of the Alternative Energy Design Toolkit. The toolkit consists of three important components: a model collection, a modeling environment, and a supporting Web site. Each of the components serves different purposes. The model collection is developed to provide models that are the fundamentals of renewable energy design. A modeling environment called DOME (Distributed Object-based Modeling Environment) is utilized as an enabler of the toolkit. The supporting Web site, which is currently underdevelopment and will soon be fully functional, serves as an information provider and a center for knowledge sharing. For all of the components, their specific functions and key characteristics are presented in detail and illustrated with examples.

In chapter 4, the solar energy model collection is presented. The solar energy collection is the first set of models developed for the toolkit, while models in other areas are still under development and soon to be added to the toolkit. The collection includes models of solar energy devices, components in solar energy systems, and solar irradiance, as well as models for analyzing solar energy systems' economics, energy efficiency, and environmental impacts. For each model, the underlying subject matter is discussed, and a description of how the model functions is provided. Furthermore, the model's accuracy and limitation of usage are also mentioned.

Chapter 5 presents two design scenarios as examples of the toolkit's applications. Design scenario *I* concerns an operation of a stand-alone photovoltaic (PV) system. Models from the toolkit are used to create a representation of the system, and the time iteration mechanism of DOME is utilized to simulate the profiles of the system's characteristics. In design scenario *II*, the performance of a hybrid PV-diesel power system is evaluated. The measures of the performance include the system's capital cost, life-cycle cost, net electricity cost, electricity production efficiency, and CO_2 emission. The design-scan analysis of DOME is used to help discover a trend of how several design variables affect the system's performance.

Lastly, chapter 6 offers concluding remarks of this thesis. Afterward, key directions and further work to be undertaken in the future are discussed.

Chapter 2

Background

2.1 Related Work

There are a number of computer-based tools developed for aiding design that involves renewable energy technologies. These range from autonomous renewable energy power systems, to integration of renewable energy technologies into existing systems, such as a building. In this section, a survey of these renewable energy design tools is given and discussed in detail. For each tool, its key capabilities, distinct characteristics, and some missing important features are pointed out. This survey is provided in order to portray the big picture of the tools in this field, which will provide context for the Alternative Energy Design Toolkit. At the end of this section, a number of observations from the survey will be made, in terms of what functions of the tools are particularly useful, and what abilities are still generally missing, etc.

Since there are a large number of renewable energy design tools available, it is more convenient to categorize the tools and discuss each category at a time. One way of categorizing these tools is by the range of renewable energy technologies that the tools incorporate in a design. In this way, the tools can be categorized into three groups: those that deal with *all*, *a few*, or only *one specific* renewable energy technologies.

2.1.1 Tools that support all types of renewable energy technologies

An example of a tool that handles virtually all renewable energy technologies is HOMER. Developed by the National Renewable Energy Laboratory (NREL), "HOMER is a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone, and distributed generation (DG) applications" [34]. The technologies for power systems that HOMER can model are photovoltaics, wind turbines, biomass, run-of-river hydro, diesel and other reciprocating engines, cogeneration, microturbines, batteries, grid, fuel cells, and electrolyzers. With these technologies options and based on a user's design scenario, HOMER seeks an optimal combination of technologies and sizes of components that would give the most cost-effective system. In addition to optimization, HOMER also provides a sensibility analysis that allows a user to see the effect of changes in the input values on the results. Even though HOMER originally stood for Hybrid Optimization Model for Electric Renewables, the current version of the tool can model systems that are not hybrid, such as standalone photovoltaic systems, as well as loads that are not electric, such as thermal and hydrogen loads [33]. With all the capabilities mentioned above, HOMER can be a powerful design tool for a wide range of renewable energy applications; nonetheless, the tool judges a design based on its economic and technical merits only [35]. It does not take into account environmental impacts of a design. The software can be downloaded for free. It has a user interface that seems easy to use and also comes with a Getting Started Guide.

Another design tool that supports consideration of a broad range of renewable energy technologies is RETScreen. RETScreen consists of a series of Microsoft Excel spreadsheets that can be used to "evaluate the energy production, life-cycle costs and greenhouse gas emission reductions for various types of energy efficient and renewable energy technologies" [41]. A standard analysis is made up of five steps: energy model, cost analysis, greenhouse gas analysis, financial summary, and sensitivity and risk analysis [41]. The tool is developed by Natural Resources Canada and, like HOMER, can be downloaded for free. Renewable energy technologies that can be considered in RETScreen are wind, small hydro, photovoltaic, solar air heating, biomass heating, solar water heating, passive solar heating, and ground-source heat pump [40]. In addition to the spreadsheets, world-wide weather data from NASA and database of renewable-energy-related products' specifications from manufacturers are also provided to assist the design process. The RETScreen International Web site also hosts Internet forums, Internet-based marketplace for linking industry and customers, and an electronic textbook that gives detailed description of the algorithms used in the tool, case studies, and background on renewable energy technologies. The detailed cost analysis sheets are very useful for a project manager to study a project's feasibility and to produce a report; however, with a large number of parameters required, RETScreen might be daunting for a novice user [54].

2.1.2 Tools that support a few types of renewable energy technologies

The tools in this category deal with designs of systems that incorporate only a small set of renewable energy technologies. For most of the tools in this group, the key technology that is always present is photovoltaic. Other technologies that are often included are wind turbines and solar water heating, together with batteries, grid, or diesel engines as power backups. With a small number of technologies in consideration, this group of tools can afford more detailed modeling of designs than the tools in the previous category. As shown in the following examples, many of the tools in this group are developed for specific tasks, and a number of different techniques are employed.

The first tool that will be discussed is a CAD/CAA tool, developed at Virginia Polytechnic Institute and State University (VT), for determining an optimal design of a hybrid wind-solar power system [7]. This tool employs linear programming techniques to minimize the cost of electricity production for a given load requirement. The renewable energy technologies considered in this tool are photovoltaic modules and wind turbines, while batteries, grid, or diesel engines are considered as backups. Based on a user's input on load demand, solar and wind resources, economic, and technical characteristics, this tool optimizes for a design that i) ensures reliable load service, ii) minimizes electricity production cost, and iii) minimizes power purchased from the grid [7]. Environmental impacts of the design are also considered, though not explicitly optimized. Namely, costs due to CO_2, NO_x, and SO_2 emissions are included in the electricity production cost to be minimized, but the amount of the CO_2, NO_x, and SO_2 emissions is not minimized explicitly.

Another approach to design a hybrid wind-solar power system is developed at Aristotelian University of Thessaloniki (AUTH). Despite the similarity in their applications, this work and the CAD/CAA tool mentioned above rely on different fundamentals. This approach is a trade-off/ risk method based on a theory of multi-objective planning under uncertainty. In this theory, "certainties can be modeled probabilistically or as 'unknown but bounded' variables without a probability structure" [16]. The approach optimizes for two design objectives: a minimum capital cost and a minimum loss of load probability. In the optimization process, simple power balance relations are computed for a large number of design scenarios. Each design scenario consists of a set of components specifications, such as rated powers of photovoltaic and wind turbine, and a set of specified uncertainties, such as load demand, wind velocity, and component availability. After all scenarios are computed, inferior designs are eliminated, and trade-off curves are plotted with the remaining robust designs, in other words, those that perform well in almost all uncertainties [16]. The trade-off curves help designers select a final design that they see as a reasonable compromise between the conflicting objectives. While the two design objectives considered in this approach are important, other significant factors, including operational characteristics, are not taken into account [7].

The next tool to be discussed is part of a project called CMRESSS (Combined Multiple Renewable Energy Sources System Simulator) in Italy. The renewable energy technologies considered in this tool are also photovoltaic modules and wind turbines, with diesel engines as backups. Unlike the previously mentioned tools, this tool is used to analyze only the transient behaviors of a power system in a standalone mode. Such transient behaviors occur during "sudden load variations, dump load insertions, and parallel operations regarding both the rotating machinery and the static converters" [5]. Studying these dynamic behaviors of the system in both normal and faulted conditions can help prevent electrical and mechanical stresses. With its specific purpose, this tool is purely a physical simulation tool, and does not concern with either economic or environmental aspects of the system design.

Another tool for designing hybrid energy systems that deals with only a small, specific set of renewable energy technologies is developed by Agricultural University of Athens (AUA) and National Technical University of Athens (NTUA), Greece. This tool is used for designing hybrid energy systems that supply both electricity and fresh water to remote areas. In addition to wind generators, photovoltaic modules, and batteries, this tool can also simulate operations of micro hydraulic plants, which serve as an energy storages as well as a reverse osmosis desalination plants [28]. Moreover, computational routines are also used for simulation of solar radiation, ambient temperature, regulator/inverter, pump, turbine, and pipeline. A distinct feature of this tool is that it determines not only the optimal combination of technologies to be utilized, but also the optimal energy management, as it sets priorities for energy production and storage for each system component.

The next example has a similar application to the previous one, namely, simulation of integrated water and power systems. A new tool is developed by SimTech and ZSW in Germany based on commercially established tools, IPSEpro and RESYSpro. IPSEpro is a modeling package that has an equation solver suitable for thermodynamic process modeling. The process simulation can be linked to the economic analysis in RESYSpro. As an extension of these tools, the new tool is "a versatile systems analysis tool for the design, performance simulation and prediction of economics of all desalination technologies and relevant power supply" [42]. The renewable energy technologies considered in this tool are also photovoltaic modules and wind turbines. Results from a case study in [42] show that the economic analysis in the tool can predict a number of detailed system costs, but it is not clear what type of ecological analysis, as claimed in the title of the article, can be performed.

The last example of tools in this category is developed specifically for use in Texas at University of Texas at Austin, called Texas Renewable Energy Evaluation Software (TREES). The tool is intended as a screening tool, rather than a design tool, for assessing economic feasibility of different renewable energy technologies [52]. The renewable energy technologies include photovoltaic modules, wind turbines, and solar water heating. Inputs required from a user are size of load, application type, location, component costs, competing fuel costs, and discount rate. As a result, the tool provides the optimal collector's area, life cycle savings, cost of electricity, and cost effectiveness index to assess economic feasibility. The tool is developed for use with Microsoft Excel spreadsheet. Since this program is only a screening tool and it only assesses economic feasibility, a more thorough tool will be needed for designing and analyzing other aspects of the system.

2.1.3 Tools that support only one specific renewable energy technology

In this category, the tools only deal with designs of systems that incorporate one specific renewable energy technology. The most popular technologies for this tool category seem to be those that are related to solar energy, such as photovoltaic modules and solar heating collectors. A number of tools in this category are discussed as follow.

The first example is a simulation tool developed in France, called SimPhoSys (Simulation of Photovoltaic Energy System). The purpose of this tool is to simulate the performance of photovoltaic energy systems, which typically consist of photovoltaic panels, a battery, a controller, an electronic converter, and an engine generator. This tool is developed in Matlab/Simulink environment, drawing advantages from its "hierarchical modular structure, the modeling of linear and nonlinear systems, and the possibility to simulate with fixed or variable time steps" [43]. The modular structure of this tool makes it highly flexible. Special attention is devoted to simulation speed and user friendliness. The outputs of this tool are graphical results of the system characteristics, such as each component's power, voltage and current, and the battery's state-of-charge. The developer identifies some optimization tasks that could be useful, such as fitting of the component model parameters, optimal sizing of the components, and optimal control of the systems; however, none of these optimizations are yet implemented in the tool.

Another tool developed for the design, planning, and simulation of photovoltaic systems is a commercial program called PV*SOL, by a Berlin based software company. Unlike SimPhoSys, PV*SOL does not emphasize on providing detailed outputs of the system's technical characteristics, such as a profile of the battery's state-of-charge. Instead, the outputs that this tool emphasizes are detailed information on power production/consumption, costs, financial return, and economic efficiency [50]. The tool also comes with data of weather in Europe and North America and commonly used system designs. Moreover, this tool also supports modeling of photovoltaic panel shading, including seasonal variance of the surroundings. With such detailed modeling, this tool is "oriented towards experienced professionals aiming to test and hone designs, and answer detailed questions" [54].

The renewable energy technology involved in the next example is a flat plate solar collector. This tool, developed at National University of Singapore (NUS), is a theoretical simulation that predicts temperature distributions of the absorber plate along the coolant channels. Overall heat loss coefficient and efficiency of a collector are determined as a nonlinear distributed model [31]. This tool is claimed to have circumvented many of the difficulties faced in other approaches in the same area. Though not directly suitable as a design tool for most users, this tool is an example of many theoretical simulations that can be more useful for research and development purposes, such as analyzing the performance of the existing technologies in order to finding a way to improve them.

Another tool that deals with solar heating collectors is developed at Murdoch University Energy Research Institute (MUERI), Australia. This tool, based on mass and energy balance calculations, is "a decision making tool in assessing suitable solar collector design options to meet the desired drying requirements" [13]. It consists of two models; one for air solar heating collectors and the other for deep bed drying systems. Based on hourly input air conditions, this tool predicts thermal performance of eight different standard designs of air heating collectors. As claimed by the developers, this tool user-oriented and can help designers understand the process of a solar drying collector, which is extremely complex.

A commercial tool for design and simulation of solar thermal heating systems is also available from the developer of PV*SOL. The tool, called T*SOL, has a built-in automatic system optimization, a performance simulator, extensive financial models, and modules for some specific applications, such as indoor and outdoor swimming pools [51]. Similar to the case of PV*SOL, T*SOL's detailed modeling makes it oriented towards experienced professionals [54].

The next example is another tool that deals with a solar-energy-related technology, a solid absorption solar refrigerator. This program is called COSSOR (COmputer Simulation of a SOlar Refrigerator) and is developed at University of Nigeria. Based on a detailed transient mathematical model of solid absorption solar refrigerator systems, COSSOR consists of about 50 subprograms representing different components of the systems [14]. This makes the program flexible and easy to manage, as each subprogram can be developed and upgraded almost independently. The program is coded in QBASIC programming language. With this tool, users can predict and analyze performance of solid absorption solar refrigerator and other thermal systems.

While the preceding examples of tools in this category show that there is a lot of effort in developing design tools for various types of solar-energy-related technologies, there are also some other tools developed specifically for other renewable energy technologies. For example, a simplified tool is built for assessing the feasibility of ground-source heat pump (GSHP) projects, as part of a free spreadsheet-based software package developed by the Canadian government [38]. The tool consists of a simplified building load model and a GSHP simulator. With this tool, designers can evaluate and perform pre-feasibility analysis on various designs.

Another tool in this category is an integrated computational environment, consisting of five connected programs. The purpose of this tool is to investigate integration of wind power into small autonomous systems, from both technical and economic point of view [21]. This tool, developed at National Technical University of Athens (NTUA), has abilities of load forecasting and management, power system analysis, and generation system simulation and planning. In other words, with this tool, a designer can obtain an optimal plan for expanding the existing system by integration of wind power, predict the economic impacts, and manage the controllable load to achieve desirable results.

The next example also deals with wind energy technology. Developed in a toolkit format, this tool is called Wind Diesel Engineering Design Toolkit. Its main purpose is to assess characteristics of small to medium sized wind systems that use diesel generators as backups [18]. The analysis of the toolkit is divided into two packages: i) dynamic simulation, including evaluations of frequency and voltage variation as well as system stability, and ii) overall performance (logistics) assessment, including evaluations of fuel savings, energy supply capabilities, and economy. The dynamic modeling package, based on simulation package CYPROS ESIM, has a modular structure, consisting of mechanical, electrical, and control component models. The modular structure permits this package to represent a wide range of system configurations. The logistics modeling package has four main elements: an input program, a suite of six models, an output program, and an executive program. The input and output programs facilitate the users in creating component specifications and graphical representations of the results, respectively. The six models are adapted from existing programs, developed by leading wind diesel experts in six European countries, to interface directly with a modeling package. With these two packages, this toolkit is capable of modeling wind diesel systems in many important aspects, but still lacks an ability to assess environmental impacts of the systems.

The last tool in this category is related to large-scale biomass technology. Based on object-oriented analysis and programming, this tool also has a form of a toolkit, named Biomass Toolkit. The toolkit consists of a number of computer programs: Beacon I, Beacon II, Biobase, Proland, ExternE, and flow-sheeting simulators. Beacon I, written in Borland C++, can analyze biomass availability, energy efficiency CO_2 emissions, and nutrient cycle. Beacon II supports integrated microeconomics approach from the farm to the final product markets. Biobase is a spreadsheet program that evaluates biomass resources on a geographical and time-dependent basis. Proland is a decision-making support tool for extreme soil erosion problems. ExternE evaluates the external costs of the biomass fuel cycles. Lastly, the flow-sheeting programs are simulators for process synthesis and design of integrated biomass conversion schemes [25]. The purpose of this toolkit is to provide "a unified approach to the problem of biomass use for energy and industry" [25]. Nonetheless, the toolkit is simply a collection of biomass-related computer programs. It is not clearly stated how the programs, if at all, are integrated or interact with each other.

2.1.4 Tools that support designs with renewable energy technologies for buildings

Rather than categorizing the existing renewable energy design tools by the range of renewable energy technologies involved, as done above, one can also categorize the tools by the technologies' applications. All the one hand, for almost all of the tools already discussed, applications of the renewable energy technologies are very broad, such as electricity generation and heat supply. More specific details of how and where the electricity and heat will be used are not critical. On the other hand, there are a surprisingly large number of design tools for utilizing renewable energy for a very specific application: buildings. The U.S. Department of Energy (DOE) has a Web directory of more than 220 building-energy software tools from around the world, most of them related to sustainable design, improving energy efficiency, and incorporating renewable-energy concepts on buildings [12]. The reason why so much attention has been paid to these areas may be that "about 50% of the energy we use today is for servicing buildings" [54]. To effectively reduce the overall, global energy consumption, energy use in buildings has to become more efficient and economical. With their potential to be efficient and economical, renewable energy technologies are therefore becoming more popular options for buildings' energy supply. The most common uses of energy in buildings are for lighting, heating, cooling, ventilation, and hot water supply. In this section, a number of tools for designs of renewable energy technologies for building applications are discussed.

The first example is developed in collaboration of the National Renewable Energy Laboratory, the Lawrence Berkeley National Laboratory, and the Berkeley Solar Group. The tool, called ENERGY-10, is conceived to provide a framework for comparing many energy alternatives for buildings before detailed design work begins [4]. This goal is achieved getting the users started at a beginning design stage with five general inputs; the inputs are location, total floor space, intended building use, number of stories, and type of heating, ventilation, and air conditioning (HVAC) system. Then, as the design process evolves, the users edit the building descriptions to be more complex. Based on hourly simulations of daylight and thermal performance, this tool has ability to automate generic building takeoffs, equipment sizing, and definition of energy efficiency strategy alternatives. The energy efficiency strategy that have already been implemented are daylighting, passive solar heating, thermal mass, HVAC controls, energy-efficient lights, shading, air leakage control, economizer cycle, glazing, insulation, high-efficiency HVAC, and reduced duct leakage [4]. As a result, the tool ranks multiple designs based on desired criteria, such as lowest annual operating cost. The developers claim that this tool can lead to a design that uses only 50% of energy and produces 50% of CO_2, NO_x, and SO_2 emissions as much as a typical building does, but costs no more to build. Though not available for free, this tool is widely bought. Online help, workshops, and training are also provided.

Another tool is developed at the University of Cambridge, called Renew. It is "a web-based tool for providing ranges of estimates for the impact of photovoltaics, solar water heating and wind turbines on building's primary energy consumption, embodied energy, energy bills and construction cost" [54]. The main purpose of this tool is to allow architects to do simple explorations of different renewable energy options in an early stage of design. The calculations done by the tool are only of first order, so other tools will be needed for more extensive modeling. Currently, the tool only covers office buildings in the UK, though an extension of building types and locations is planned. Since this tool is intended as an exploration tool and no optimization function is provided, users need to use a trial-and-error approach in their designs.

While the tools in the previous examples deal with explorations of renewable energy alternatives, the tools in the following examples deal more specifically with lighting and thermal aspects of buildings. Developed at FEDIC International Federation of Consulting Engineers, one tool consists of advanced simulators of lighting control technologies [26]. Efficient controls of daylight and artificial lighting can be obtained. The tool also aims to help reduce the use of electricity for cooling and ventilation, and increase visual comfort of office buildings. A similar tool is also developed at Fraunhofer Institute for Solar Energy Systems (ISE) in Germany. This tool also has computer simulators for analyzing daylight features, as well as thermal performance of buildings [3]. CAD data of buildings can be input into the linked lighting and thermal simulations. As a result, different integrated lighting-thermal concepts can be evaluated.

Simulations of thermal and lighting performance of buildings become more complicated for high-rise buildings and housing clusters, where one building can significantly affect the performance of another. To investigate the relationship among buildings in a housing cluster, a 3D computer modeling tool is developed in Yemen. This tool analyzes solar access and shading in buildings with respect to their forms, the sun location, and the times of the year [2]. The tool helps assess different methods for controlling the lighting and thermal components of buildings. As a result, rules of thumb in formats of architectural designs can be developed for housing clusters.

Another tool deals with interior lighting in high-rise buildings. This tool is a commercial program called Lightscape. This tool is useful for comparing different lighting options and varying design to meet lighting requirements of different building orientations with different solar considerations [8]. Detailed modeling of buildings, such as sizes of columns and beams, and configuration of ceilings relative to window glazing internal daylight, is crucial.

The last example of tools for building-energy design is Integrated Building Design System (IBDS), part of the EU COMBINE project (COmputer Models for the Building INdustry in Europe). In IBDS, a number of simulation and design tools are integrated via object-oriented data models [10]. The tools that have been integrated are related to building regulations, costing, component databases, daylight and energy, EU standards, and CAD systems [9]. Although these separate tools have already been used by design professionals, COMBINE's goal is to bring these tools together so that "skilled experts can continue to work with specialized tools," while at the same time, "information about all aspects of the project will remain transparent to all players" [9].

The key characteristics and features of all the surveyed tools are summarized in the appendix, where the tools are denoted by their names or, if they do not have a formal name, by their developer's name.

2.2 Identification of challenges

2.2.1 Observations from the surveyed tools

The followings observations are made from the survey, presented in the previous section, of the existing tools for designs with renewable energy technologies.

- While a tool like RETScreen provides detailed descriptions of models and algorithms used, most of the other tools do not expose their underlying models to the users. Without knowledge of the underlying models, the users have a less chance of understanding the issues faced in their designs and may have a difficulty in achieving their designs' goals.
- For all of the tools in the examples given, the underlying simulation models are fixed. The users are not allowed to modify or substitute the models with other models that they might find more suitable; even though, such ability can be highly desirable from a research and development standpoint.
- Some tools have a modular structure or a toolkit style that allows the users to flexibly model or design a system by integrating different component models or programs supported in the tools. Nonetheless, the variety of the supported models or programs is limited, and the users cannot incorporate outside models or programs into the tools. Since it is impossible to include all models a priori, the ability to allow the users to incorporate other models or programs is quite critical if the developers do not want to limit the application scope of their tools.
- Some tools, such as Renew, require only a small number of inputs from the users. Most of the values used for the underlying models are default values set by the developers of the tools. In contrast, some tools, such as PV*SOL, require extremely detailed inputs that can be daunting to some users. None of the tools have an ability to provide different user interfaces for multiple levels of complexity.
- The tools that involve designs with only a few or one specific renewable energy technologies mostly have a functionality dedicated for simulating of physical properties, such as battery voltage, building's thermal performance, and biomass resource availability, etc. Such

simulations of physical properties, however, are not emphasized in screening or first-order design tools like TREES and Renew.

- Only a few tools are developed primarily for public access and user-friendliness. In particular, while RETScreen and HOMER can be downloaded from their Web sites, Renew is the only tool in the survey that is readily executable via the Internet.
- Some tools are based on a spreadsheet program and make use of its interface that is easy to use and familiar to most users. However, this dependency means that the users have to possess the specific spreadsheet software and figure out how to work within the details of the spreadsheets.
- The tools can indirectly influence the designs. For examples, the tools that support designs with only a few or one specific renewable energy technologies can make the designers unintentionally focus only on those technologies that are supported by the tools. Some tools provided a database of specifications of system components. While convenient for the design process, the database can also limit the designers' choices to only a specific set of components.
- An environmental impact assessment is a key functionality that is lacking in most of the tools. In fact, among all of the surveyed tools, only two of them, HOMER and ENERGY-10, have a dedicated analysis on environmental impacts of a design.
- A number of tools have an optimization functionality that can be very useful and save the users from trails and errors in their design process. However, the design objectives of the optimizations are often fixed and limited. For example, the CAD/CAA tool by Aristotelian University of Thessaloniki only optimizes for a design with a minimum capital cost and lost of load probability. Other costs like operational and life-cycle costs cannot be optimized.
- On the one hand, an optimization mechanism in some tools provides the users with only one optimal design, while concealing the other designs that it deems inferior. In this way, the tools implicitly make the final design decision in stead of the users. On the other hand, an optimization in some tools provides a number of options to the users. The provided

options are often in a form of a trade-off curve or a ranked list. This way, the tools only suggest several highly favorable alternatives to the designers, and the final design decision still belongs to the designers.

- To promote collaboration in a design process, RETScreen provides online forums and a marketplace for their users to communicate and share knowledge. Wind Diesel Engineering Design also takes advantage of experts from different fields by including a number of programs developed by them in the tool. However, among all the surveyed tools, IBDS (Integrated Building Design System) is the only tool that truly supports collaborations among designers and experts directly in a design process. In a collaborated design, IBDS lets designers work with the tools of their expertise. While only working on their specialized aspects of the design, the designers can also observe the other aspects and learn about what each other are doing. Nonetheless, IBDS only supports designs with integration of renewable energy technologies in buildings.
- The technologies that are the most associated with in all tools are those related to solar energy, while the application that has the most tools developed for is the building-energy application.

2.2.2 Lessons learned

In order to develop a powerful tool for aiding designs associated with renewable energy technologies, a number of characteristics and capabilities should be possessed by the tool, as discussed below.

- Detailed descriptions of models used in the tool should be accessible to the users, so that they can understand the underlying mechanisms of their designs.
- The users should have freedom to select, try out, and replace any models that they utilize in their design process.
- The tool should support multiple levels of complexity of user interfaces, so that user interactions in the design process can be tailored toward specific user groups and, hence, be effective.

- The tool should have simulation mechanisms that can support all type of simulations, such as physical properties, economics, etc.

- Public users should be able to easily use and access the tool. One way to make the tool accessible to most people is to make it available through the Internet. In addition, the tool can also be convenient to use if the users can use it directly off the web without having to download and install it onto their computers.

- Provided that most users are familiar with a spreadsheet format, the tool should utilize it, however, without relying on particular spreadsheet software.

- The tool should be able to incorporate any types of models and programs, including environmental analysis models, into a design process, so that the tool does not affect the scope of the design.

- A modular or toolkit-styled structure can enable the tool with a flexible modeling mechanism that can work well even with models or programs from outside the toolkit.

- In order to avoid a trail-and-error process and to achieve an effective design, an optimization mechanism should be integrated in the tool. The optimization should be flexible enough that the users can set any types of design objectives. Furthermore, to reserve final design decisions for the users, the optimization should suggest a group of robust design options, instead of one option that the tool considers optimal. This can be achieved if the optimization's results are presented in forms of trade-off curves or a ranked list.

- The tool should have a mechanism that allows multiple designers and experts to directly and actively collaborate in a design, by allowing them to work in their specialized fields, while also having an ability to be informed about activities in other parts of the design. In addition, some forms of online forums or marketplaces should be provided with the tool, to also promote communications among designers from different design projects.

- Lastly, the tool should allow new representations of systems to be built in an ad-hoc fashion, and enables them to be expanded easily and flexibly.

In the next chapter, the Alternative Energy Design Toolkit will be discussed in details, and the characteristics and capabilities discussed above will be emphasized more clearly.

2.3 DOME

DOME (Distributed Object-based Modeling Environment) is an innovative software infrastructure that is used as a key enabler for the Alternative Energy Design Toolkit. Developed by the CADlab at MIT, DOME is a Web-based, simulation modeling environment that supports emergent and integrated design processes. Users of DOME can quickly create simulations for large integrated systems and predict likely characteristic before implementing prototype systems [53].

DOME is an implementation of the world-wide simulation web (WWSW) concept. The WWSW is analogous to the world-wide web (WWW) in a way that it lets people share their own and discover others' ideas [53]. More specifically, the WWSW allows people to express their ideas and knowledge in forms of models, both mathematical of geometric. People can learn and develop upon others' ideas to create a new idea, as they study and built upon, or integrate, others' models to produce a new model. This process is much similar to how people discover others' Web pages, make links to them, and add more contents to generate a new Web page.

In addition to allowing the models to be universally accessible through the internet, DOME also supports flexible integrations of models. When creating an integration, DOME users only need to create a connection between two models in a declarative fashion. In other words, the users do not have to specify how the information would flow from one model to another. The directions of information flows are automatically determined during the simulation time. In addition, a central solver is also not required for solving the integrated system. Instead, DOME relies on an emergent solving mechanism, in which the individual models act as autonomous, local solvers. When the simulation is executed, the individual models share their own internal causality, which defines the dependency of the parameters within each model. The shared causalities enable each model to figure out when it should solve itself, hence, eliminating the need for a central solver. Furthermore, DOME supports a distribution of resources. That is, models in an integration are not required to be on the same server. With the distributed property, integrations in DOME can be expanded extensively, and the computational limit of resources becomes less an issue.

Furthermore, models developed in third-party software can also be easily wrapped and utilized in DOME. Also, for any model or integration of models, multiple user interfaces can be provided to tailor to specific needs of different groups of users. All of the user interfaces come with a standard, spreadsheet-like, look, so that the end-users can use any models without having to spend extra time to learn to use them. In addition to the standard look, customized graphical user interfaces (GUI) can also be added to a DOME interface, in order to organize and present the parameters in an alternative appearance.

A section in the next chapter will provide more information about the attributes of DOME in details and show how they help propel the Alternative Energy Design Toolkit toward its goal.

Chapter 3

Alternative Energy Design Toolkit

3.1 Overview

The Alternative Energy Design Toolkit consists of a collection of mathematical models, a software infrastructure called DOME, and a web site. The models are mathematical representations of fundamental elements of renewable energy technologies. The key enabler of the toolkit, DOME, which stands for Distributed Object-based Modeling Environment, is a simulation modeling environment that supports an emergent, decentralized approach in integrated design processes [53]. The last component of the toolkit is a web site that holds web forums and detailed descriptions of the models in the toolkit. All three components of the toolkit will be discussed in more details in the upcoming sections.

The main goal of the Alternative Energy Design Toolkit is *to provide a widely accessible, easy to use, flexible, yet powerful modeling environment for assisting collaborated and integrated design that associates with renewable energy technologies, while also promoting knowledge sharing among users.* With this goal, all of the desired characteristics and capabilities identified at the end of the previous chapter are embraced. The goal is achieved with help from all three components of the toolkit collectively. The following sections discuss each component and how it helps accomplish parts of the goal.

3.2 Model Collection

The model collection consists of high quality simulation models representing a diverse range of elements found in energy systems. Designers can pick any models from the collection and integrate them to produce a representation of any designs or systems. For example, a model that represents a photovoltaic (PV) panel and another model for a lead-acid battery are included in the toolkit. A designer can pick these two models and integrate them to create a representation of a very simple PV power system. The means of integrating models together will be explained in the next section when DOME is discussed. Helping achieve the main goal of the toolkit, the model collection has the following major desired characteristics:

3.2.1 Usability of the models

Models of fundamental components commonly used in renewable energy design processes are readily available from the toolkit. These models can help expedite design processes by saving the designers from having to spend time creating their own representations the components. The designers can jump start their design processes with the provided models and spend more time configuring each component and integrating all components together. For instance, as mentioned earlier, the toolkit includes a model of a lead-acid battery, which is a common component in most PV power systems. The model contains mathematical relations for predicting the battery's voltage and state-of-charge for a given current and specifications. Instead of having to work out or to model these relations at the beginning of their design processes, designers can instantly use the available model and proceed to the next step, such as configuring the battery's specifications.

3.2.2 Modular structure

Each model in the toolkit is a modular entity and can function independently. In fact, the models that represent components of renewable energy systems function as though they are the actual components themselves. For example, the model that represents a PV panel functions like an actual PV panel; that is, when some solar irradiance input is provided to the model, it yields some electricity output, and the value of its temperature parameter rises. Being able to use each model independently, designers can then work on each component of systems in their designs separately, resulting in a more efficient design process, since a design of one component does not affect the others, and designs of multiple components can be conducted simultaneously.

The modularity of the models also allows designs to evolve easily. In any system designs, the designers can effortlessly replace one component model with another, as long as the interfaces required to connect to the models are compatible. For instance, in a simple power system that consists of a PV panel and a battery, the designer may learn from simulation results that the PV panel does not deliver satisfactory performance, and may wish to try other types of generators. The designer can simply replace the PV panel model with, for example, a wind generator model, as the interfaces required for connecting to the battery model are matching, namely the output current and the terminal voltage. The design process of the power system then becomes flexible. Together with DOME's declarative and emergent characteristics, the modularity of the models can help facilitate changes in designs and encourages designers to be creative and explore more alternatives.

Besides flexibility, the modular nature of the models also provides high reusability. Since the models are developed so that they can function independently, and not specifically intended for any simulations, they can be reused in any applicable integrations. For example, one user can use the model for predicting global irradiance on an inclined surface to predict the amount solar irradiance for a PV power system simulation. If another user wants to have the same prediction for a simulation of a flat-plate thermal solar collector, he can reuse the predicting model from the PV system simulation, without having to rebuild a new model specifically for his simulation. The modularity of the model provides reusability that helps expedite the design process.

3.2.3 Multiple forms of user interfaces

Many of the models in the toolkit have multiple forms of user interfaces tailored for different usages. This idea is similar to the concept of constructor overloading in an object-oriented programming language. The overloading provides multiple constructors with different signatures for a given class [46]. Each of the constructors is tailored toward a specific use situation, so that the utilization of the class is more effective. Likewise, the multiple interfaces help make utilizations of the models more effective and less confusing. Generally, most models contain more than one mathematical relations, or functions, dealing with different, interrelated issues. For example, a model representing geometric relationships between the sun and the earth contains many functions that deal with several issues, including calculation of the sun's position and the times of sunset and sunrise, etc. Having only one interface for all users to interact with the model is impractical for many reasons. Firstly, some users may need to use only one specific function of the model. It might be confusing and inefficient if they have to use an interface that is also associated with other functions. As in the case of the sun-earth relationship model, some users might only want to use the function for calculating the solar declination[1], which exclusively varies with the day of the year. An interface that requires only the day number as an input, and provides the solar declination as an output would be sufficient for these users. However, if this interface is also associated with, for instance, a function for calculating sunrise and sunset times, other inputs like latitude and longitude would also be required as inputs to the interface. Consequently, the users might misunderstand that latitude and longitude are in some way affecting the solar declination. With too many input and output parameters from many functions in the model all tangled up in one interface, the users might be confused of the real, underlying dependencies. Thus, in some cases, having multiple interfaces serving different, independent functions of the model can help avoid the confusion.

Secondly, it is impractical to have only one interface for some models that may be utilized by users from different backgrounds. For example, users that are technically oriented would be more comfortable with an interface requiring technical specifications than the general users would. Thus, even to access the same function in the model, multiple interfaces with different levels of complexity can help make a design process more efficient. Lastly, for some models, even if the same function is accessed by users of the same technical background, it might be impractical to have only one interface, since the function may be used in different scenarios. For example, a model representing an inverter[2] in the toolkit has two interfaces. Both interfaces are used to access the same function in the model, namely, a calculation of required current

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[1] Solar declination is the angle between the earth-sun line and the plane through the equator. This tilt is the major cause of seasonal variation of the availability of solar radiation. The solar declination varies from -23.45° at winter solstice (December 21st) to 23.45° at summer solstice (June 21st). The value is at 0° at fall and spring equinoxes (September 21st and March 21st, respectively).

[2] An inverter is a DC/AC converter.

and power for given voltage and output power. However, the two interfaces require different additional inputs from the users. One interface asks for values of load and copper resistances, and transformer and circuit losses, assuming that these values are known by the users. The other interface is intended for use in another scenario, when the values of resistances and losses are unknown, but loss coefficients of the inverter are provided by the manufacturer. These interfaces are tailored for uses in different, specific scenarios and help make the utilization of the model more effective.

3.2.4 Minimal third-party software dependencies

In order to minimize dependencies on third-party software, mathematical relations in almost every model in the toolkit are written and executed using a built-in mathematical functionality of DOME, even though they can be written and executed with any software. Developed on Jython[3] and a few Java mathematical packages, DOME's built-in functionality can perform all kinds of mathematical computations required by the models in the toolkit, with the only exception of implicit equation solving, which has been planned but yet implemented in DOME. In that case, the models that require implicit equation solving are written and executed using MATLAB[4]. Nevertheless, this only means that the server[5] that hosts these models, as well as users who wish to modify these models, must have MATLAB. The other users of the toolkit still do not need MATLAB for executing or integrating these models in their designs. Consequently, unlike some of the tools surveyed in the previous chapter, the toolkit has the least dependency on third-party software and can be utilized more widely. Furthermore, this dependency can later be totally eliminated when implicit equation solving is implemented in DOME.

3.2.5 Coverage of key elements

To ensure that key elements necessary for most renewable energy designs are well covered in the toolkit, a lot of effort is put into the model collecting process. The collecting process starts

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[3] Jython is an implementation of object-oriented language Python written in Java, so that Python can be run on any Java platform [20].

[4] MATLAB is a high-level technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numerical computation [30].

[5] Details about model servers will be disscussed in the following section.

with a study of background of renewable energy technologies. For each technology, the most important step is identifying the key elements, or components often included in the designs. For instance, the key components in designs with photovoltaic (PV) power technology are PV panels, a battery, a controller, and an inverter. Once the components are identified in the study, the model collecting process continues with an extensive search of mathematical models that represent those components. After the component models are selected, other aspects of the designs also need to be considered. The two aspects that ought to be specially emphasized are the economics and environmental impacts of the designs. For these aspects, the key elements or issues, such as life-cycle cost and toxic gas emission, are also identified; and models related to the issues are searched. In some occasions, models of some key components or elements are not available. Fortunately these models involve only simple logic and can to be constructed without too much difficulty for the toolkit. An example is a model for determining minimal power of PV panels and capacity of batteries required for a given electricity load demand. With the key elements well covered, the toolkit can support a wide range of designs associated with renewable energy technologies.

3.2.6 Reliability and validation of models

In the model collecting process for the toolkit, most of the models were found in scientific journals or technical books. To make certain that the models are reliable, validations of the models are necessary. In most cases, the models published in scientific journals and books are accompanied by a validation either in a form of a comparison to experimental results or a reference to other literatures if they are widely known. These models are considered reasonably reliable. Some models are published in more than one equally reliable source, and each one may be slightly different from another, even though they represent the same components or issues. In that case, the models are presented as different interfaces in one model in the toolkit, and the users have a freedom to use any of them. Furthermore, some models are reliable in only certain design scenarios, as stated by the models' publishers. The statements are included with the models' description available from the toolkit's Web site, so that the users can use those models accordingly.

Even though all of the models in the toolkit are deemed reliable, users may still find that some of the models can be improved. Allowed to help improve and contribute to the toolkit, the users can make copies of the models, modify them for better accuracy or performance, and keep them as the users' own versions of the models, or also submit them to the toolkit Web site to be reviewed and added to the toolkit. In this fashion, the reliability of the models in the toolkit can also be validated and increased by the users.

3.2.7 Extensibility and knowledge sharing

Other than improving the existing models, users can also contribute more models to the toolkit. This ability is very beneficial for the expansion of the toolkit, since it can become an expedient means to fill in what the toolkit lacks. Users such as experts from different disciplines, as well as researchers of related projects, can contribute models that they have already developed, so that the usual, time-consuming and tedious process of model collection can be avoided when possible. With DOME as a key enabler of the toolkit, model contributions become trouble-free, given that models developed in any software can easily be made ready for the toolkit[6]. The toolkit's ability to allow the users to easily contribute their models not only helps make the toolkit significantly expandable, but also promotes collaboration and knowledge sharing among experts from different fields.

Currently most of the existing models of the toolkit are related to solar energy technologies. Models related to other types of renewable energy technologies are under development and will be constantly added to the toolkit. The existing solar energy models of the toolkit will be discussed in the next chapter.

3.3 DOME

Another component of the toolkit is the third generation of a software infrastructure called DOME (Distributed Object-based Modeling Environment). As already mentioned, DOME is a Web-based, simulation modeling environment that supports emergent and integrated design

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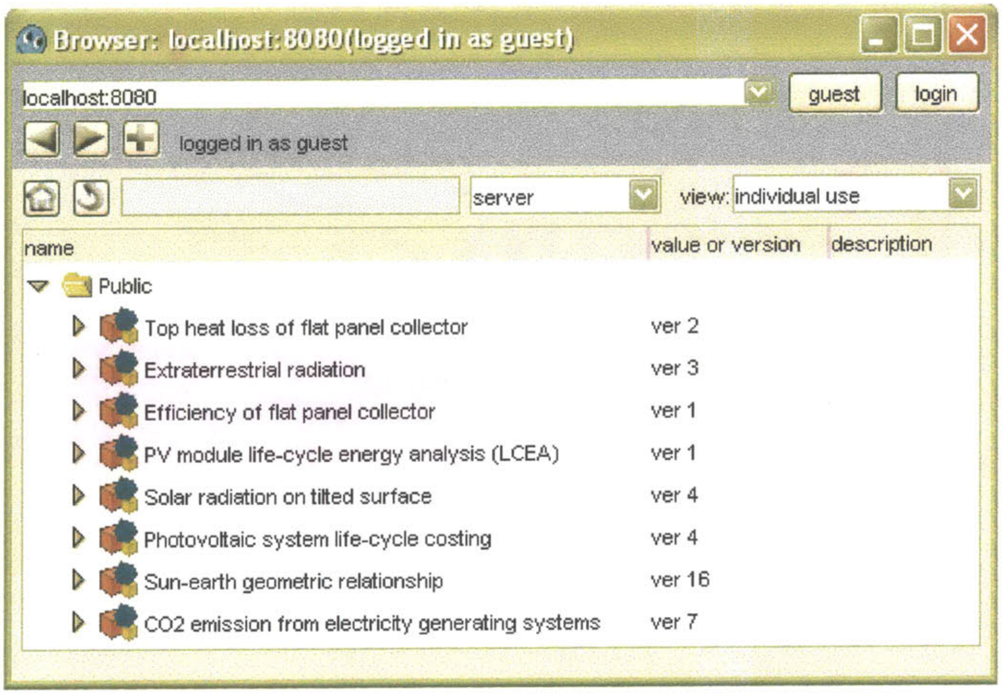
[6] Details of how models developed in other softwares are wrapped in DOME and made ready for integration with other models will be disscussed in the next section.

processes. Employing DOME as the key enabler, the toolkit can advance toward its main goal by taking advantages of the following capabilities and characteristics of DOME:

3.3.1 Accessibility through the Internet

To discover and run models through the internet, a user has to login to a DOME server[7] through a DOME *run browser*, which is similar to a Web browser such as Internet Explorer or Netscape. The run browser is part of the DOME application, which is available for any user to download and install on a local computer. However, DOME has another capability that further increases accessibility of the tool. Namely, DOME can be set up as an applet, a Java application that can be run in a Web browser. Consequently, any user with an Internet access can go to a Web site that has a DOME applet and use DOME without having to install the application on his machine. The Alternative Energy Design Toolkit makes use of this capability, so that any user



localhost:8080

server

view: individual use

name	value or version	description
Public		
Top heat loss of flat panel collector	ver 2	
Extraterrestrial radiation	ver 3	
Efficiency of flat panel collector	ver 1	
PV module life-cycle energy analysis (LCEA)	ver 1	
Solar radiation on tilted surface	ver 4	
Photovoltaic system life-cycle costing	ver 4	
Sun-earth geometric relationship	ver 16	
CO2 emission from electricity generating systems	ver 7	

Figure 3-1: DOME run browser.

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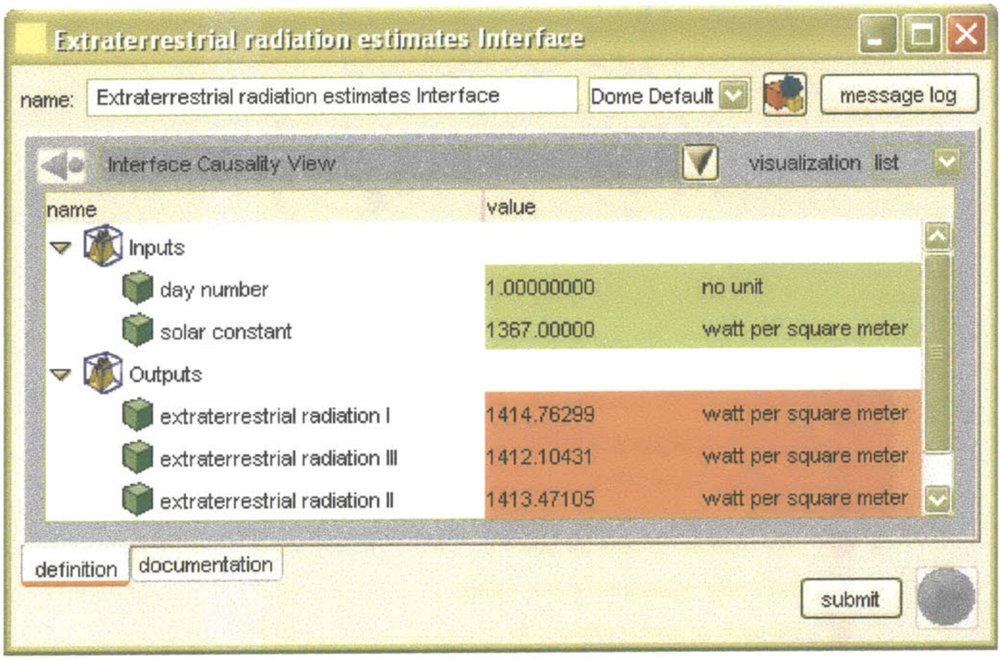
[7] Currently, a user needs to know the IP address of the DOME server to connect and login. A model search mechanism is under development and will soon be available.

can browse and use the models in the toolkit directly from the toolkit's Web site, making the toolkit widely accessible.

3.3.2 Multiple interfaces for end-users

All models in DOME have a standard user interface, shown in figure 3-2, that eliminates the need for a user to learn how to run a model every time a new model is used. When an interface is opened, the parameters are automatically loaded with default values, originally set by the model's developer. In case of the models in the Alternative Energy Design Toolkit, the interfaces' parameters are pre-configured with typically practiced values. This way, any user may run the models without knowing all the input values, and can still get reasonable results. Furthermore, the standard interface has a spreadsheet-like visualization that is familiar to most users. To run a model, a user can change values of the inputs, press the submit button, and see new values of the outputs. Other than the spreadsheet-like visualization, the standard interface also offers two more types of visualizations: graph and design system matrix. (See figures 3-3 and 3-4). These two visualizations provide end users information of how parameters in a model



name: Extraterrestrial radiation estimates Interface

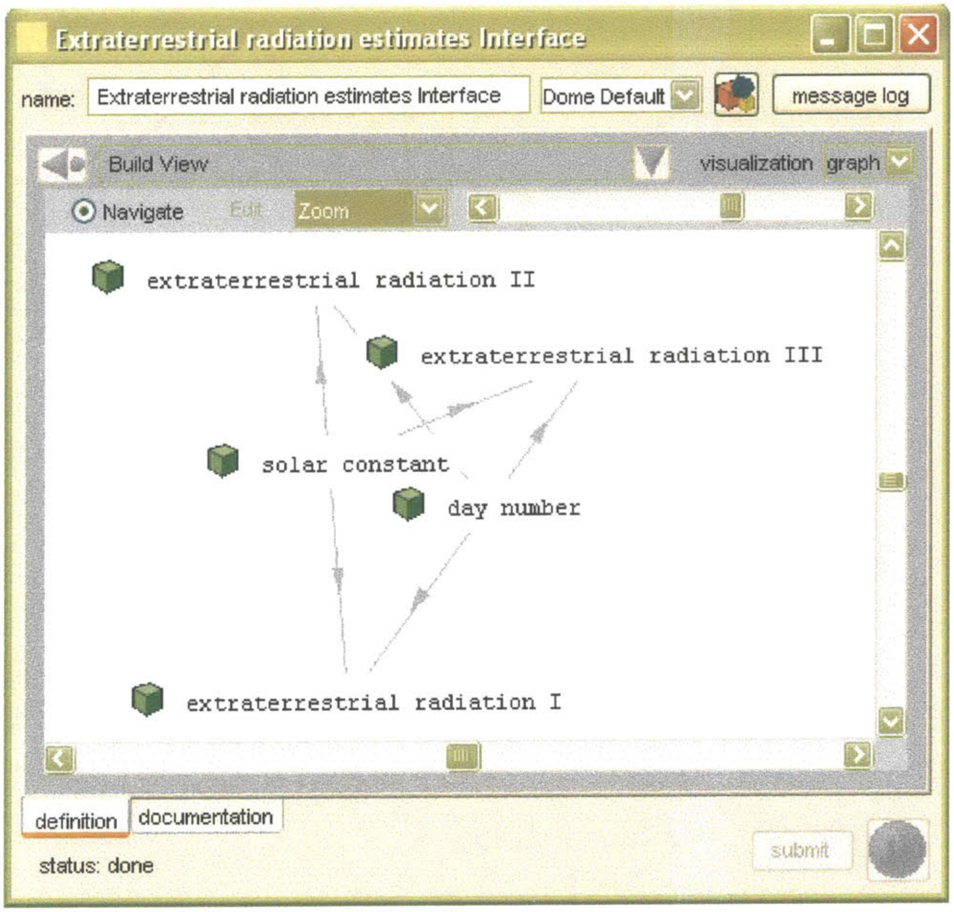
visualization: list

name	value	
Inputs		
day number	1.00000000	no unit
solar constant	1367.00000	watt per square meter
Outputs		
extraterrestrial radiation I	1414.76299	watt per square meter
extraterrestrial radiation III	1412.10431	watt per square meter
extraterrestrial radiation II	1413.47105	watt per square meter

Figure 3-2: Standard user interface of a model.

are related to one another.

Besides a standard interface, a customized interface can also be created and linked to a model. Any model developer can create a customized interface, using Java Swing[8] components, to provide more contents, including related pictures and comments, to the users. Thus, in addition to delivering an appearance that the developer wants, a customized interface can also help make the model easier to understand for the users. Figure 3-5 shows an example of a customized interface. With the three standard visualizations and an option to create a customized interface offered in DOME, the models in the Alternative Energy Design Toolkit can be made easier to use and understand.



Extraterrestrial radiation estimates Interface

name: Extraterrestrial radiation estimates Interface

Dome Default

Build View

visualization graph

○ Navigate

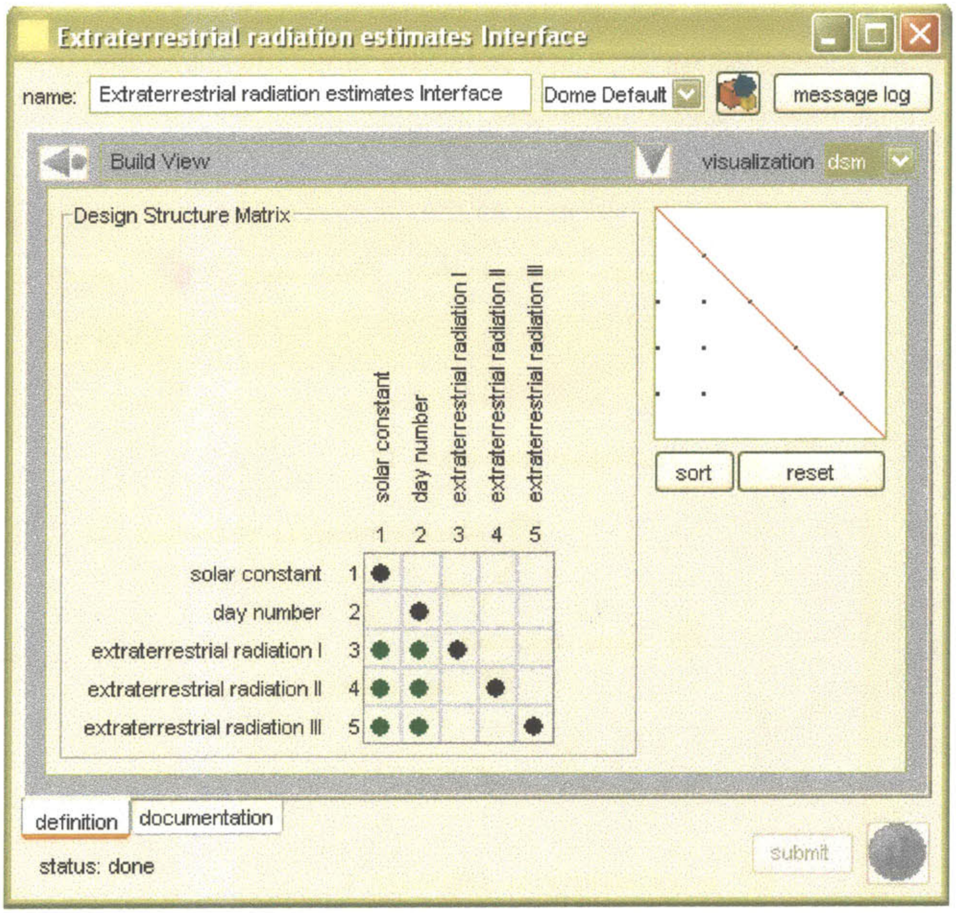
Zoom

status: done

Figure 3-3: Graph visualization in a standard interface.

---

[8] Swing is a project for lightweight graphical user interface (GUI) components in Java Foundation Classes [47].



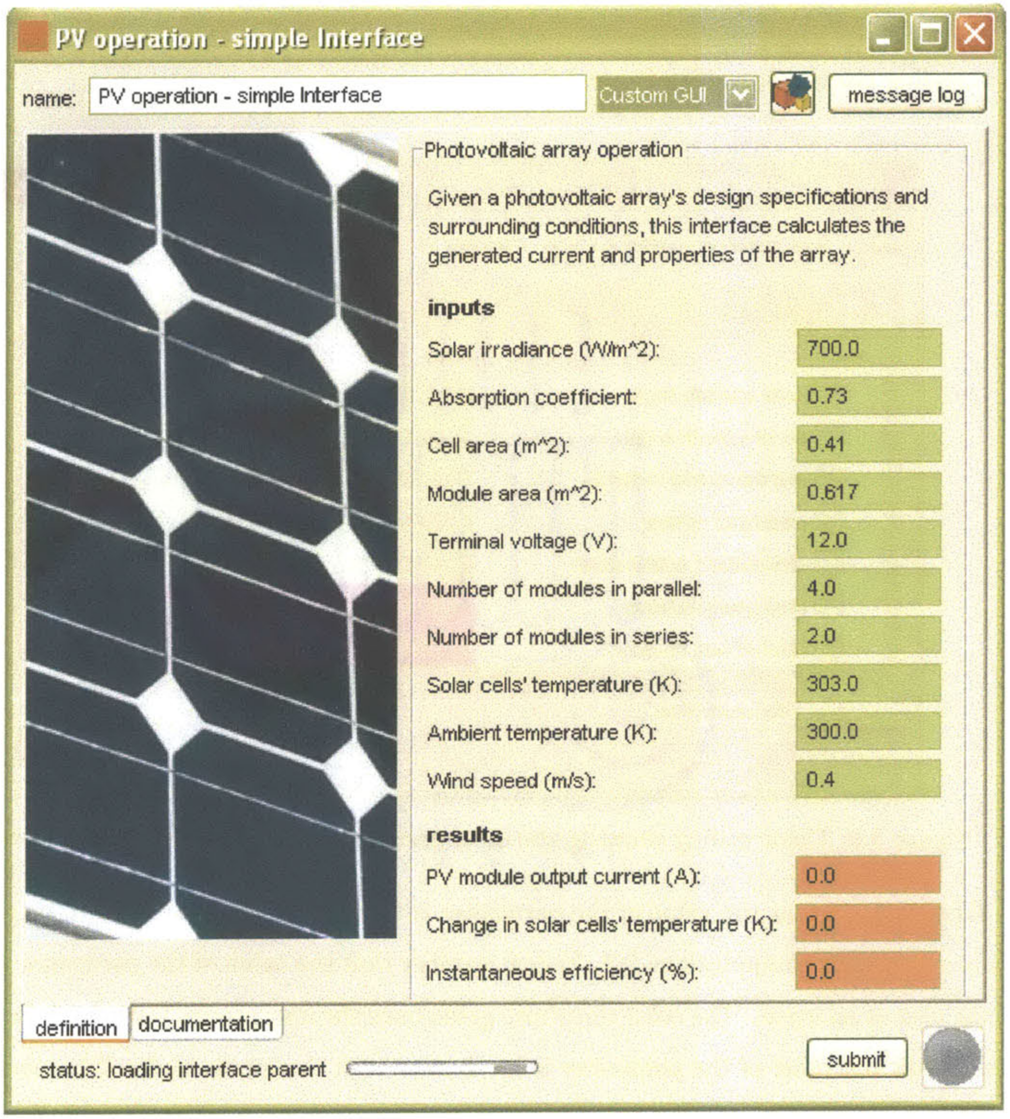
name: Extraterrestrial radiation estimates Interface

visualization: dsm

		solar constant 1	day number 2	extraterrestrial radiation I 3	extraterrestrial radiation II 4	extraterrestrial radiation III 5
solar constant	1	●				
day number	2		●			
extraterrestrial radiation I	3	●	●	●		
extraterrestrial radiation II	4	●	●		●	
extraterrestrial radiation III	5	●	●			●

status: done

Figure 3-4: Design system matrix visualization of a standard interface.



name: PV operation - simple Interface

Photovoltaic array operation

Given a photovoltaic array's design specifications and surrounding conditions, this interface calculates the generated current and properties of the array.

inputs

Solar irradiance (W/m^2): 700.0

Absorption coefficient: 0.73

Cell area (m^2): 0.41

Module area (m^2): 0.617

Terminal voltage (V): 12.0

Number of modules in parallel: 4.0

Number of modules in series: 2.0

Solar cells' temperature (K): 303.0

Ambient temperature (K): 300.0

Wind speed (m/s): 0.4

results

PV module output current (A): 0.0

Change in solar cells' temperature (K): 0.0

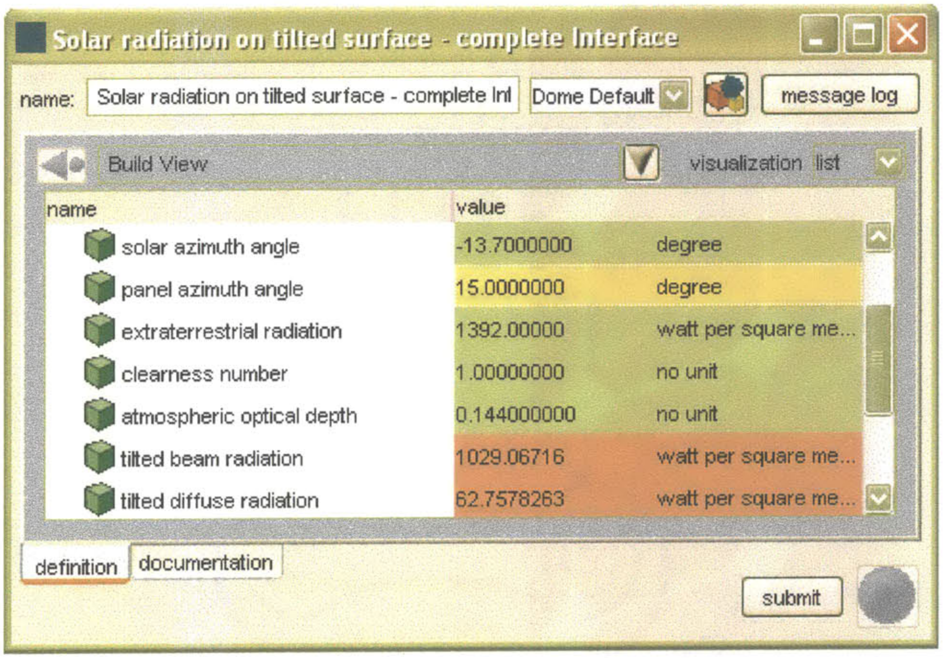
Instantaneous efficiency (%): 0.0

status: loading interface parent

Figure 3-5: Customized interface.

3.3.3 Computation-status feedback for end-users

DOME provides live feedback on status of computations. Live feedback can be particularly useful for a simulation that takes a long time to finish and involves a large number of parameters and models, which is often a case in a design associated with renewable energy technologies. During a computation, users can notice the status of a parameter's value from the color coding surrounding the number. (See figure 3-6).



name: Solar radiation on tilted surface - complete Int

Dome Default

visualization: list

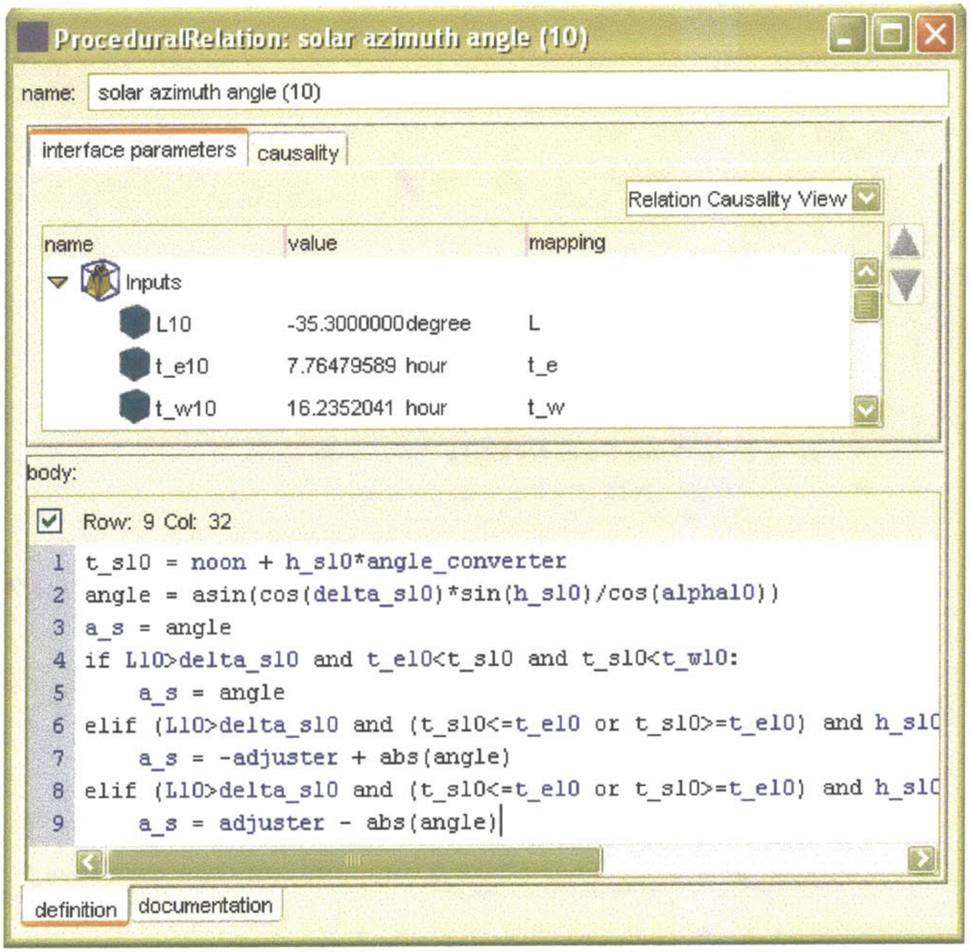
name	value	
solar azimuth angle	-13.7000000	degree
panel azimuth angle	15.0000000	degree
extraterrestrial radiation	1392.00000	watt per square me...
clearness number	1.00000000	no unit
atmospheric optical depth	0.144000000	no unit
tilted beam radiation	1029.06716	watt per square me...
tilted diffuse radiation	62.7578263	watt per square me...

Figure 3-6: Color coding showing status of parameters' values during a computation.

Green means that the value of the parameter is up-to-date, but may need to be rolled back if any subsequent computations fail. Yellow signifies that the value of the parameter is changed by the user as an input. The color turns into green once the user presses the submit button. Red means that the value of the parameter is incoherent with the inputs and will be updated later in the computation. Lastly, White means that the value is final. With the feedback mechanism, users of the Alternative Energy Design Toolkit can determine which values are reliable in real time, resulting in more transparent and comprehendible design process.

3.3.4 Implementation of new models

An implementation of a new model can also be done with DOME. As mentioned in the previous section, DOME has a built-in mechanism the supports most of mathematical operations, including iterations. When participants of the Alternative Energy Design Toolkit develop a new model, they can conveniently implement and test mathematical relations of the model within DOME, eliminating the need for third-party programming software.



name: solar azimuth angle (10)

name	value	mapping
Inputs		
L10	-35.3000000degree	L
t_e10	7.76479589 hour	t_e
t_w10	16.2352041 hour	t_w

body:

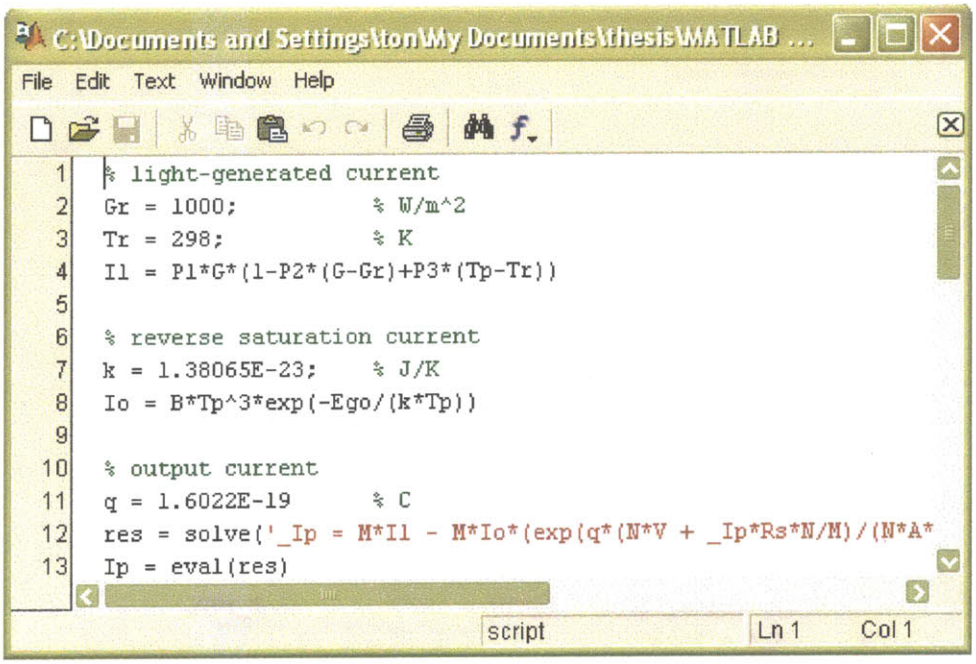
☑ Row: 9 Col: 32

```
t_sl0 = noon + h_sl0*angle_converter
angle = asin(cos(delta_sl0)*sin(h_sl0)/cos(alphal0))
a_s = angle
if L10>delta_sl0 and t_el0<t_sl0 and t_sl0<t_wl0:
    a_s = angle
elif (L10>delta_sl0 and (t_sl0<=t_el0 or t_sl0>=t_el0) and h_sl
    a_s = -adjuster + abs(angle)
elif (L10>delta_sl0 and (t_sl0<=t_el0 or t_sl0>=t_el0) and h_sl
    a_s = adjuster - abs(angle)
```

Figure 3-7: Built-in mathematical programming mechanism in DOME.

3.3.5 Wrapping of third-party models

DOME has a mechanism that allows developers to easily wrap models originally developed in any third-party softwares. The wrapping makes models utilizable in the DOME context and can be done without any programming. For example, to wrap a model originally written as a MATLAB script (figure 3-8), the developer only needs to create a new model in DOME, add parameters to the model, and specify references to the associated MATLAB variables (figure 3-9). While wrapping the model, the developer can make use of the dimension checking mechanism of DOME, by specify a unit to each parameter. Consequently, the model can become more robust after being wrapped, since a dimensional check might not be support in the software where the model is originally created, such as MATLAB or Excel.



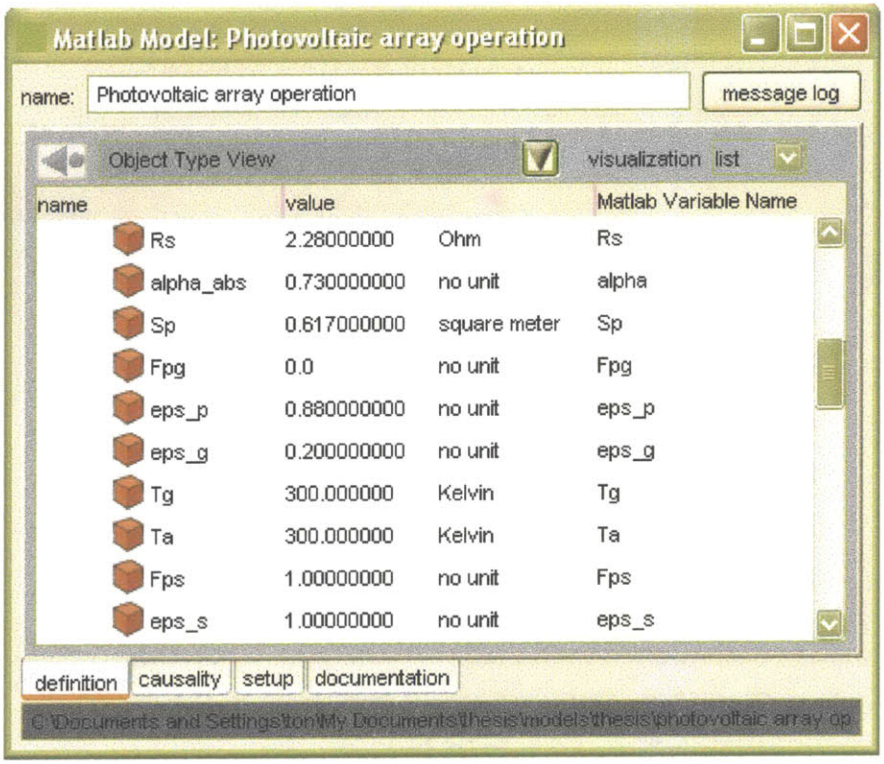
```
% light-generated current
Gr = 1000;              % W/m^2
Tr = 298;               % K
Il = P1*G*(1-P2*(G-Gr)+P3*(Tp-Tr))

% reverse saturation current
k = 1.38065E-23;        % J/K
Io = B*Tp^3*exp(-Ego/(k*Tp))

% output current
q = 1.6022E-19          % C
res = solve('_Ip = M*Il - M*Io*(exp(q*(N*V + _Ip*Rs*N/M)/(N*A*
Ip = eval(res)
```

Figure 3-8: Matlab script.

The wrapping process can be done quickly, and after that the model can be deployed and ready to be use in the DOME context like any other models. This ability of DOME is critical for the Alternative Energy Design Toolkit, since the operation of the toolkit involves participations of experts from different fields, who are likely to have developed their models in many, different software. The ability to have all types of models easily wrapped and usable in the DOME context can make collaborations among the experts go smoothly.



name: Photovoltaic array operation

name	value		Matlab Variable Name
Rs	2.28000000	Ohm	Rs
alpha_abs	0.730000000	no unit	alpha
Sp	0.617000000	square meter	Sp
Fpg	0.0	no unit	Fpg
eps_p	0.880000000	no unit	eps_p
eps_g	0.200000000	no unit	eps_g
Tg	300.000000	Kelvin	Tg
Ta	300.000000	Kelvin	Ta
Fps	1.00000000	no unit	Fps
eps_s	1.00000000	no unit	eps_s

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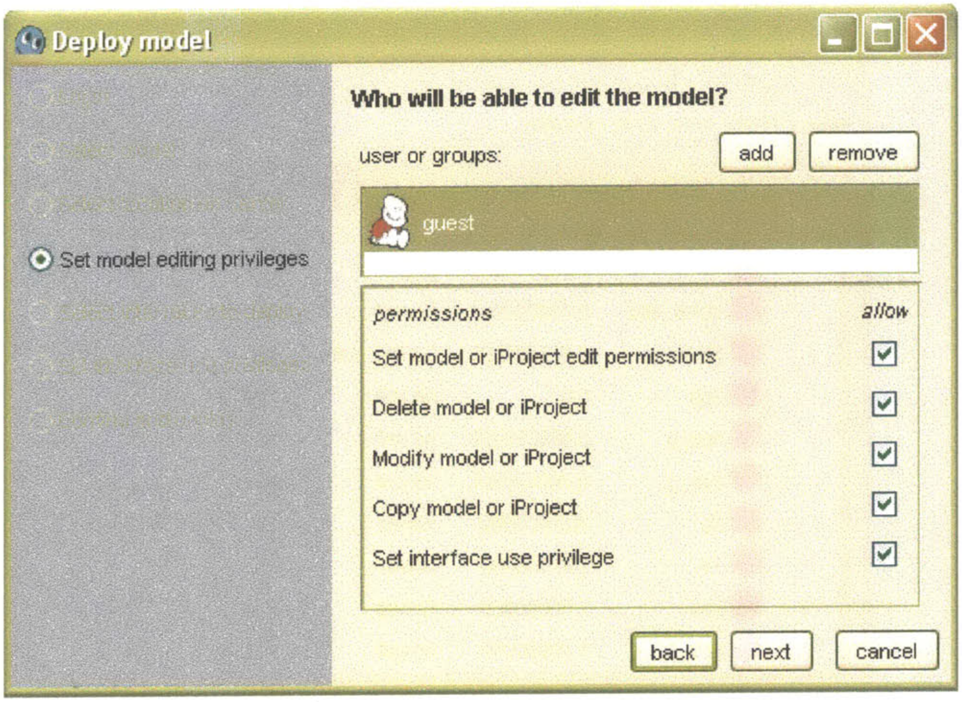
Figure 3-9: Wrapped MATLAB model with references to the variables in the original script.

3.3.6 Deployment and permission settings

Once developed and ready to be used, a model can be made available to users by getting deployed on a DOME server, in a similar fashion to a Web page being uploaded to a Web server. After deployed, the model is *online* and can be accessed via the Internet by anyone who has a proper permission. Different types of permissions can be set for a model by the developer during the deployment. (See figures 3-10 and 3-11). In particular, the developer can decide to make the model accessible to only specific users or groups, or all *guests*[9]. The access permission of the user is determined and the run browser displays a list of models accordingly. In case of the Alternative Energy Design Toolkit, all models are set to be accessible to all guests.

---

[9] Guest is a login mode that does not require a password. Anyone can login as a guest. However, a guest does not have his own private file space on the server like other regular users and, thus, cannot deploy any models.



○ Set model editing privileges

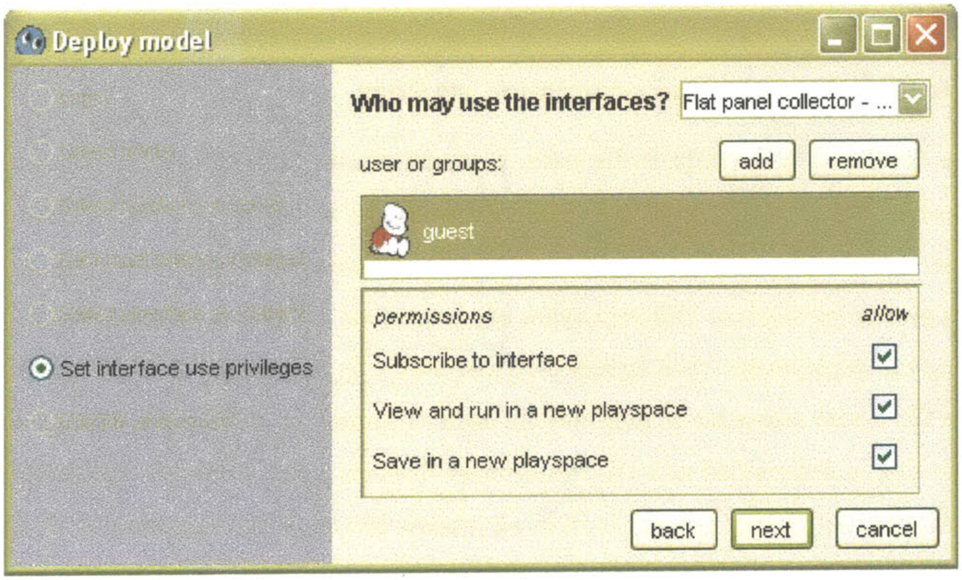
Who will be able to edit the model?

user or groups:

guest

permissions	*allow*
Set model or iProject edit permissions	☑
Delete model or iProject	☑
Modify model or iProject	☑
Copy model or iProject	☑
Set interface use privilege	☑

Figure 3-10: Setting of editing permissions during deployment.



○ Set interface use privileges

Who may use the interfaces? Flat panel collector - ...

user or groups:

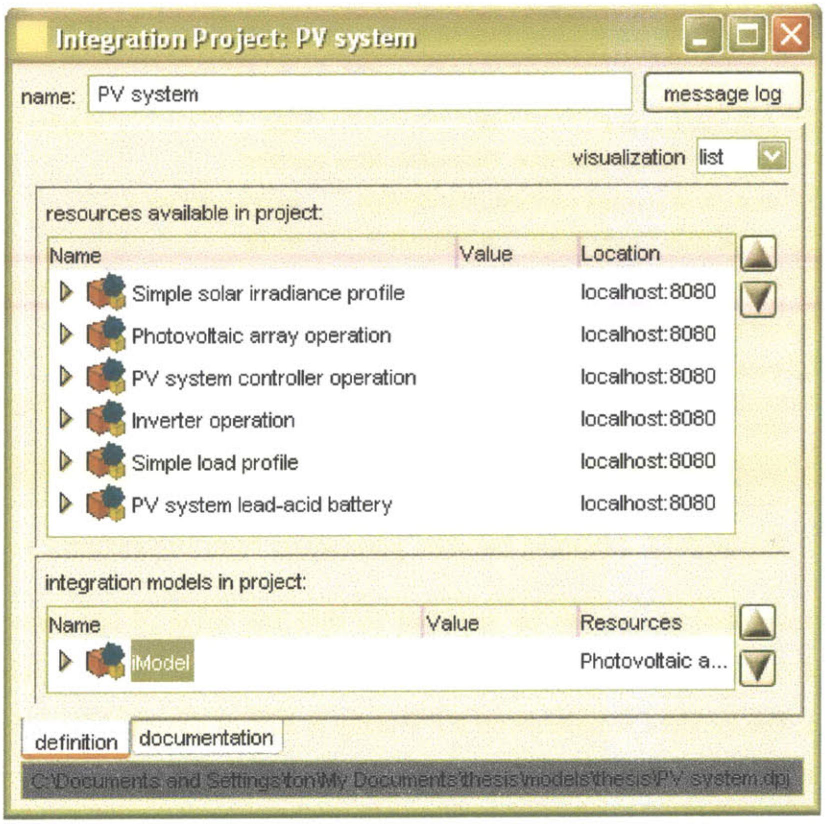
guest

permissions	*allow*
Subscribe to interface	☑
View and run in a new playspace	☑
Save in a new playspace	☑

Figure 3-11: Setting of use permissions during deployment.

3.3.7 Model integration

Users of the Alternative Energy Design Toolkit can easily create integration of models in DOME. To start, a user needs to browse through DOME servers to locate *resource* models for the integration. When a model is located, the user then *subscribes* to that live resource model. The subscription only creates a reference to the resource model and stores information necessary for the integration. The actual resource model, however, is not copied or moved from the DOME server where it is originally deployed. This way, proprietary of the resource model is still preserved, while the capability of the model can be shared. After all resource models are subscribed, the user then makes links between parameters in the resources using an integration model.



name: PV system

visualization: list

resources available in project:

Name	Value	Location
Simple solar irradiance profile		localhost:8080
Photovoltaic array operation		localhost:8080
PV system controller operation		localhost:8080
Inverter operation		localhost:8080
Simple load profile		localhost:8080
PV system lead-acid battery		localhost:8080

integration models in project:

Name	Value	Resources
iModel		Photovoltaic a...

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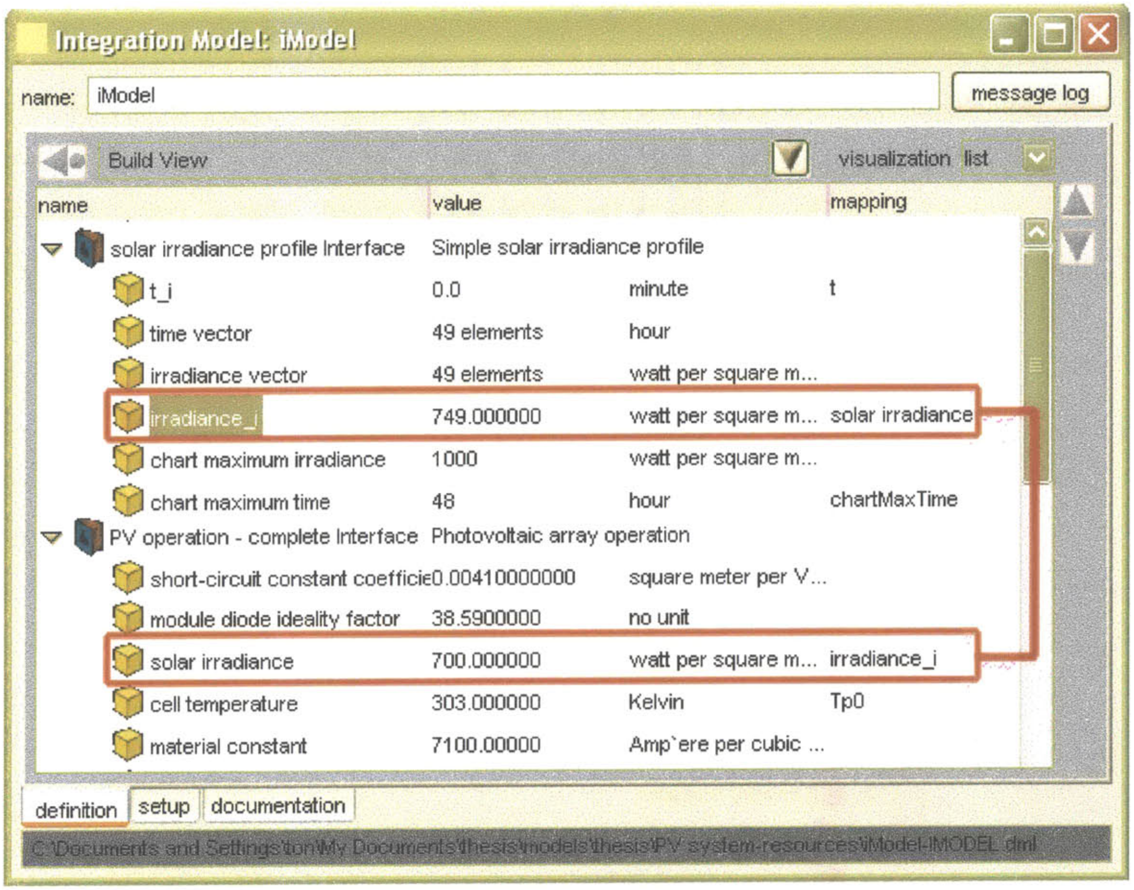
Figure 3-12: Integration consisting of six resource models and one integration model.

A link between two parameters, from any of the resource models, can be made in two forms: a direct mapping or a mathematical relation. A direct mapping makes the value of one parameter consistent with that of the other. For example, the user can specify that the value of incident irradiance on a PV array should always be consistent with the available solar irradiance. The mapped parameters are highlighted in figure 3-13. On the other hand, a mathematical relation can also be specified so that the value of one parameter is always a function of the other. For instance, instead of creating a direct mapping above, the user can specify that the incident irradiance on a PV array is 85% of the available solar irradiance. The ability to specify a mathematical relation between parameters of integrated models is a unique mechanism of DOME that is rarely provided in any other modeling tools with a similar modular structure, such as Simulink.



name: iModel

visualization: list

name	value		mapping
solar irradiance profile Interface	Simple solar irradiance profile		
t_i	0.0	minute	t
time vector	49 elements	hour	
irradiance vector	49 elements	watt per square m...	
irradiance_i	749.000000	watt per square m...	solar irradiance
chart maximum irradiance	1000	watt per square m...	
chart maximum time	48	hour	chartMaxTime
PV operation - complete Interface	Photovoltaic array operation		
short-circuit constant coefficie	0.00410000000	square meter per V...	
module diode ideality factor	38.5900000	no unit	
solar irradiance	700.000000	watt per square m...	irradiance_i
cell temperature	303.000000	Kelvin	Tp0
material constant	7100.00000	Amp`ere per cubic ...	

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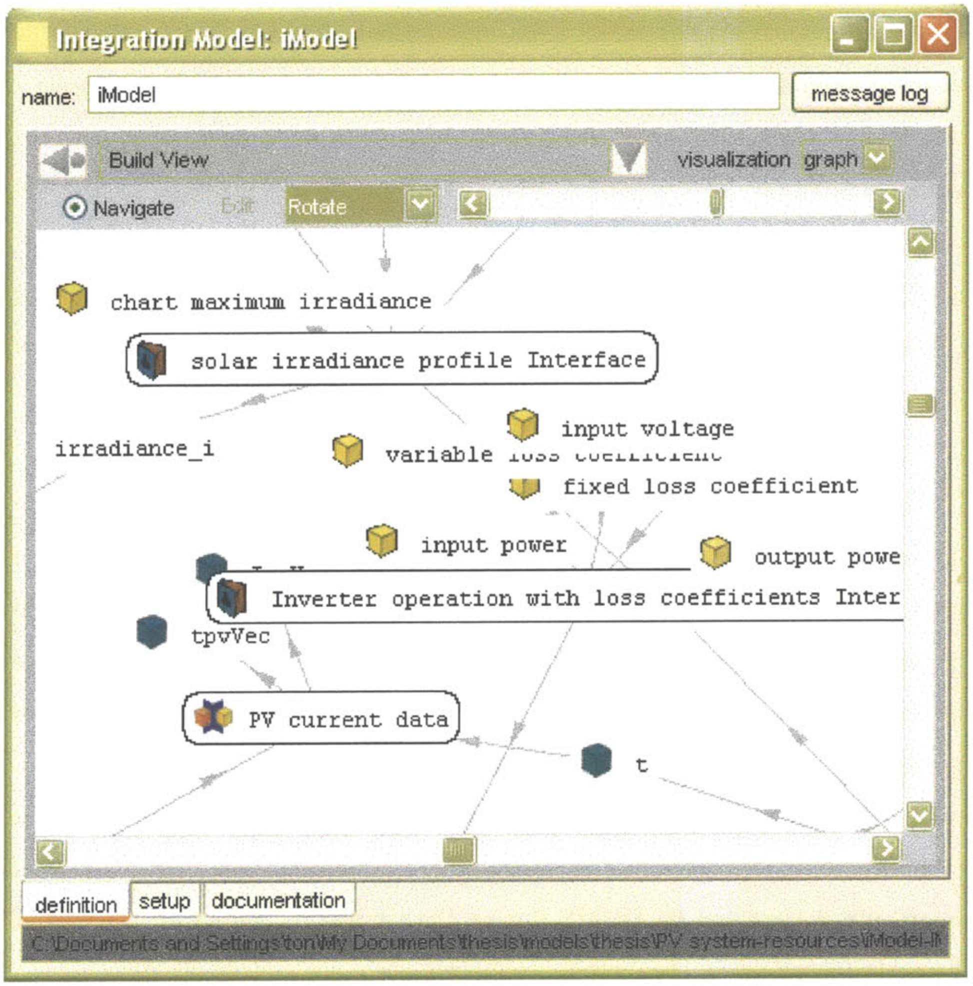
Figure 3-13: Mapping between parameters from two resource models.

In addition, once models are integrated, a graph visualization of DOME can provide a visual validation of the connections within the overall integration. This is particularly useful for a large integration. (See figure 3-14).


Integration Model: iModel

name: iModel

visualization: graph

C:\Documents and Settings\ton\My Documents\thesis\models\thesis\PV system-resources\iModel-I

Figure 3-14: Graph visualization of a large, integrated project.

3.3.8 Computation with distributed resources

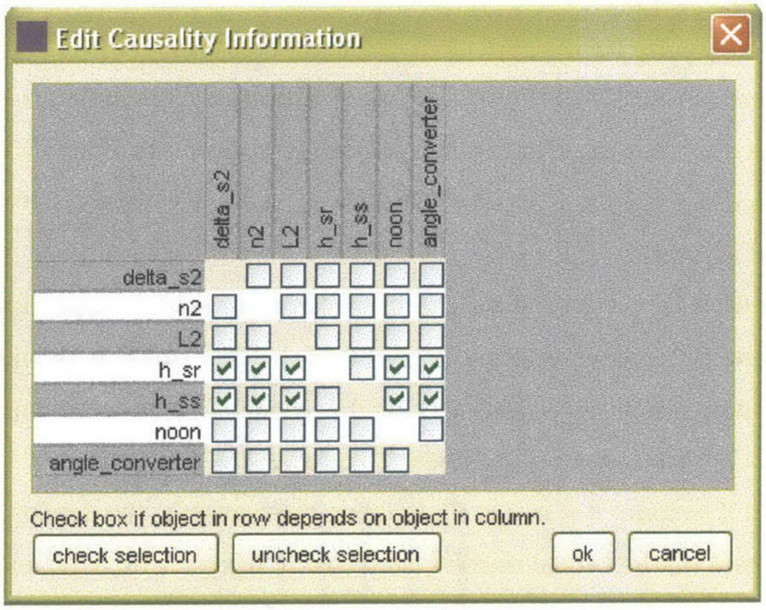
In the DOME context, resource models used in an integrated simulation can be *distributed*, that is, they are not required to be on the same computer or server. Regardless of where the resource models reside, all integrated simulations operate in the same way. In fact, for a large, integrated design simulation, a distribution of resource models on multiple servers may achieve a higher performance than a consolidation of all models on a single server. That is because, during a simulation, models are executed by their host servers, not by the computer from which the end user runs the simulation. Therefore, having many resource models of an integrated simulation consolidated on one server may overload the server and slow down the simulation.

More importantly, the capability to support distributed resource models helps facilitate incremental expansions of an integrated design. In other words, different users can continue contributing to an existing integrated design without having to worry about over-expanding the integrated simulation. This capability that DOME provides is essential for the Alternative Energy Design Toolkit because models contributions from various experts are highly encouraged. Some of the experts will prefer to keep their models on their own servers for a proprietary reason. With the toolkit's distributed capability, proprietary of the resource models are preserved, while the models can still serve as resources for the toolkit.

3.3.9 Declarative model integration and parameter mappings

While building an integrated simulation in the DOME context, a user can make a connection between models in a *declarative* fashion, that is, without the user having to specify a direction of the information flow, or dependency, between the models. In fact, the only dependency that a user ever needs to specify is the causality of parameters within a mathematical relation, when each individual model, including an integration model, is being built (figure 3-15). Thereafter, as well as when the models are put together, the user never has to specify any other dependency information. Specifically, the direction of information flow between the models will be automatically determined by DOME during the simulation, based on the causality from the mathematical relations in the models.

For the example in the previous subsection (figure 3-13), the causality within each mathematical relation of all individual models is already defined when the models are developed. When they are put together, no dependency or direction of the information flow between the models need to be specified, and a connection is made declaratively. Such as, when the solar-irradiance-profile model is integrated with the PV-array model, the user only needs to declare that the irradiance parameters of both models are consistent, by mapping them together. The direction of the information flow between the two parameters, and effectively the two models, will be automatically determined when the simulation is executed. In this case, DOME will figure out from the models' causalities that the irradiance parameter of the PV model is an



	delta_s2	n2	L2	h_sr	h_ss	noon	angle_converter
delta_s2		☐	☐	☐	☐	☐	☐
n2	☐		☐	☐	☐	☐	☐
L2	☐	☐		☐	☐	☐	☐
h_sr	☑	☑	☑		☐	☑	☑
h_ss	☑	☑	☑	☐		☑	☑
noon	☐	☐	☐	☐	☐		☐
angle_converter	☐	☐	☐	☐	☐	☐	

Check box if object in row depends on object in column.

Figure 3-15: Causality information of parameters in a mathematical relation.

input, while the one of the profile model is an output. Therefore, the information will flow from the irradiance-profile model to the PV model. More examples of declarative model integrations will be given in the next subsection.

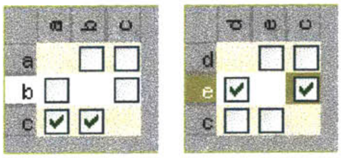
The declarative model integration can help prevent complexity of a design process, since the users only need to manage the information flow within each mathematical relation, which is the lowest and the easiest to handle level. The information flows at higher levels, such as between models or integrated systems, are automatically handled by DOME. Since designs associated with renewable energy technologies often require a number of integrations between models and systems, having to pre-configure a lot of information flows at different levels can be highly complicated and troublesome. With DOME as the key enabler, this problem is prevented from the toolkit.

3.3.10 Solving mechanism

DOME solves parametric relations of an integrated simulation using an *emergent*, or on-the-fly, approach. As discussed earlier, dependency information for all levels of connections, except within mathematical relations, of an integrated simulation is automatically determined by

DOME during a simulation. However, such emergent solving of the dependency information is not achieved by any central system coordinator. Instead, DOME relies on the individual models as autonomous, local solvers. When the integrated simulation is executed, the model share causality information with the ones connected to them. The causality information shared among the models is only a portion sufficient to make the models solve their dependencies correctly and efficiently.

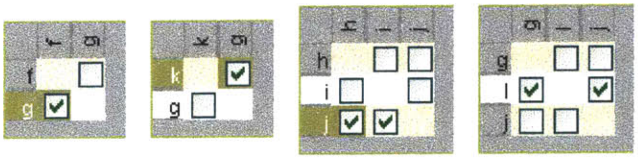
The benefits of the emergent solving mechanism are hard to appreciate, unless a detailed example is given. Thus, an example of an integrated simulation is provided here. This integrated simulation consists of models X, Y, and Z. Model X contains the following mathematical relations: $c = a + b$ and $e = c \times d$. Model Y contains $g = f/2$, $j = h + i$, $k = g$, and $l = g - j$. Lastly, model Z contains $o = m + n$. In building these models, the developer has to specify the causality of each mathematical relation, as shown in figures 3-16, 3-17, and 3-18.



	a	b	c
a		☐	☐
b	☐		☐
c	☑	☑	

	d	e	c
d		☐	☐
e	☑		☑
c	☐	☐	

Figure 3-16: Causality information for model X.



	f	g
f		☐
g	☑	

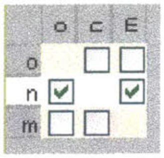
	k	g
k		☑
g	☐	

	h	i	j
h		☐	☐
i	☐		☐
j	☑	☑	

	g	l	j
g		☐	☐
l	☑		☑
j	☐	☐	

Figure 3-17: Causality information for model Y.

The above causalities are all that the user has to specify in terms of dependency information. Based on the causalities of each model, DOME automatically determines the dependency information for the models as shown in figures 3-19, 3-20, and 3-21. Now the models are ready to be integrated. Suppose the user declaratively maps k to m, e to n, and a to l. DOME then determines, based on the dependency information above, that the information should flow from k to m, e to n, and l to a. Note that each model is still autonomous and unaware of the



	o	n	m
o		☐	☐
n	☑		☑
m	☐	☐	

Figure 3-18: Causality information for model Z.

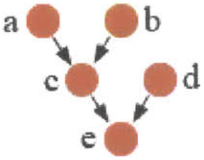


Figure 3-19: Dependency information of model X.

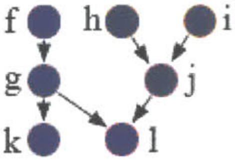


Figure 3-20: Dependency information of model Y.

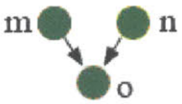


Figure 3-21: Dependency information of model Z.

dependency information of the other models.

Once the simulation starts, the models need to share the necessary dependency information with each other. Figures 3-22, 3-23, and 3-24 show the information shared by the models. After the dependency information of the models are shared, DOME's emergent solving mechanism combine all the information (see figure 3-25) and notify the models of any necessary external dependency information they need to know. Finally, the models have all necessary information to solve themselves efficiently and correctly (see figures 3-26, 3-27, and 3-28). This example of integrated simulation demonstrates one of the most crucial benefit of the emergent solving mechanism. That is, the model Z now knows that its m and n parameters are correlated. Therefore, it should wait for the new values of both m and n before executing the $o = m + n$ relation, instead of doing it twice. This benefit can be extremely useful for the Alternative Energy Design Toolkit as the relation might be a highly complicated computation that takes a long time to finish. It would be inefficient to execute that computation redundantly. Moreover,

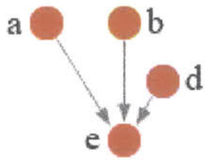


Figure 3-22: Dependency information shared by model X.

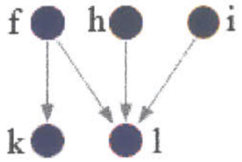


Figure 3-23: Dependency information shared by model Y.

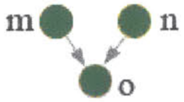


Figure 3-24: Dependency information shared by model Z.

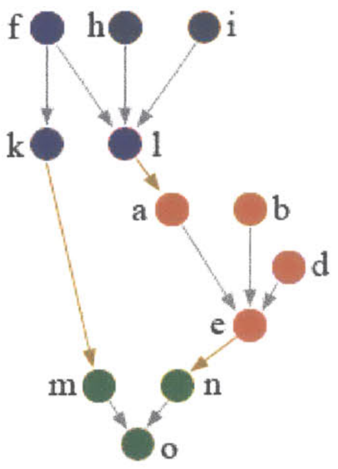


Figure 3-25: Complete dependency information collected by DOME, based on the information shared by all models.

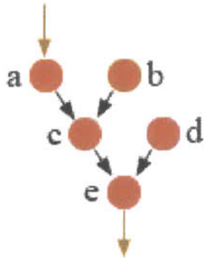


Figure 3-26: Dependency information for model X to autonomously solve itself.

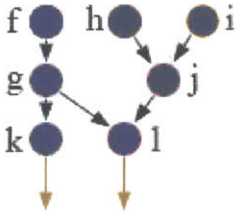


Figure 3-27: Dependency information for model Y to autonomously solve itself.

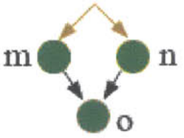


Figure 3-28: Dependency information for model Z to autonomously solve itself.

the emergent solving mechanism of DOME also makes a design process of an integrated system more flexible, since the user does not have to explicitly plan the order in which the mathematical relations should be executed.

3.3.11 Collaborative design

Besides a conventional, independent design, which a user work on individually, DOME also supports a live, collaborative design through a collaborative work space, called *playspace*. A playspace allows multiple users to simultaneously work together on the same models or integrated simulations of designs. One user would see results of any changes that the other users make on the design in the playspace. The users can also discuss with each other via a built-in chat tool.

Making use of this capability of DOME, the Alternative Energy Design Toolkit can provide the experts from different fields with another means to contribute their knowledge. That is, in addition to providing their models to the toolkit, the experts can use a playspace to input their opinion on a design, discuss problems, and try out different options together on a live design simulation.

3.3.12 Informed decision making with an optimization tool

DOME includes an optimization tool called Queuing Multi-Objective Optimiser (QMOO) [55]. QMOO is an evolutionary algorithm, which is ideal for multi-objective optimizations in energy systems because these systems are often non-linear, discontinuous, multimodal, and hard to resolve [27]. QMOO is capable of converging to difficult-to-find optima and exploring the full extent of the problem's optimal regions. Test cases show that QMOO has performs better than earlier optimization methods.

This optimization tool is highly useful for the Alternative Energy Design Toolkit for many reasons. The first reason is, it helps the users identify optimal design options much faster than using the conventional trail-and-error approach. Secondly, it has features tailored for the nature of energy system optimization problems. Lastly, it is developed for multi-objective problems, which are frequently faced in the designs associated with renewable energy technologies. For example, in a design of PV-diesel hybrid power system, the designer has to deal with, at least, two competing objectives: the system's cost and greenhouse gas emission. If the system relies heavily on PV panels, then the cost could be high, while the emission is low. On the other hand, if the system relies on diesel generators, then the cost could be lower, but the emission will likely be higher. With the design of this system modeled in DOME, the user can use the optimization tool to obtain a number of optimal options, plotted on a trade-off curve (see figure 3-29). After that, the user has a freedom to choose any of the option that suits the design's situation. With the optimization tool, users of the toolkit can make their design decision in an informed and effective fashion.

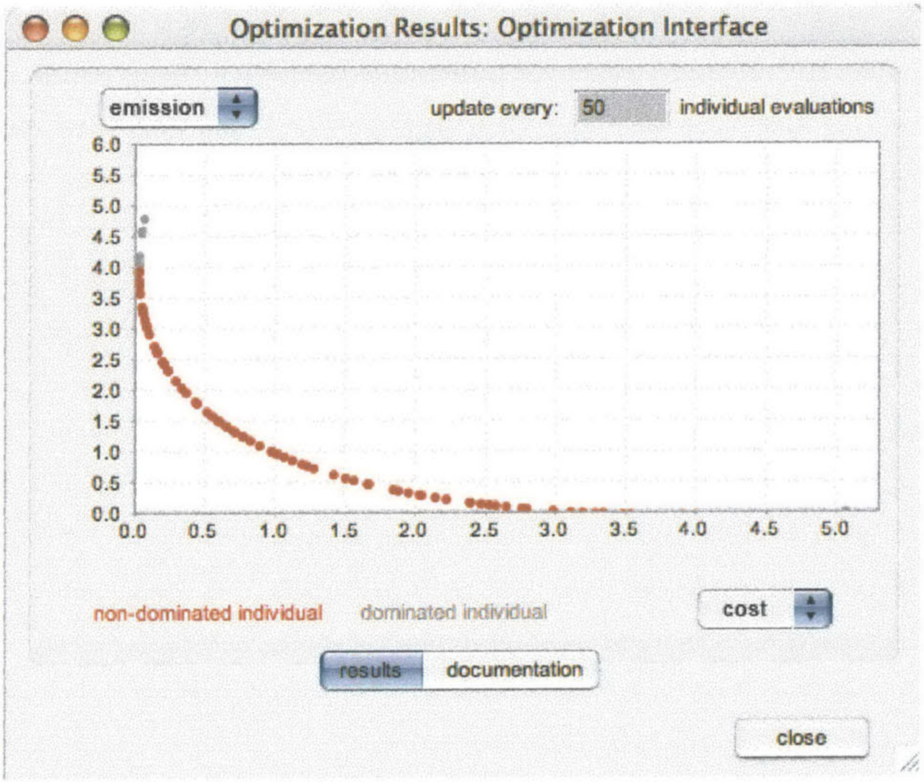


Figure 3-29: Trade-off curve plotting various optimal options (red dots).

With all the capabilities discussed in this section, DOME is very much suitable as an enabler for the Alternative Energy Design Toolkit. It helps advance the toolkit closer to its main goal, especially in the aspects of flexibility and power in collaborated and integrated designs.

3.4 Supporting Web site

The third, and last, component of the Alternative Energy Design Toolkit is a supporting Web site. This Web site serves many purposes, but mostly are to enhance the accessibility and easy-to-use aspects of the toolkit's main goal. Each of the following subsection discusses each of the Web site's functions individually.

3.4.1 Bridge between the WWW and the WWSW

As already mentioned, DOME is an implementation of the world-wide simulation web (WWSW) concept, which is analogous to the world-wide web (WWW). Even though the WWW and the WWSW are both accessible to anyone through the Internet, at the present time, the WWW is much more widely accessible. That is because the WWW has been established and known for a longer time, and the tools used for accessing the WWW, such as many varieties of Web browsers, are easily available to everyone. In contrast, the WWSW is still in its early stage and unheard of by most people, and, unlike Web browsers that are preinstalled on most computers, DOME run browser necessary for accessing the WWSW is still not widely possessed by many people.

Therefore, in case of the Alternative Energy Design Toolkit, to deliver to the people the ideas and knowledge enclosed in the models of the WWSW, a bridge is needed to make the WWSW accessible from the WWW, where people access extensively. The toolkit's supporting Web site serves as that bridge. People can roam in the WWW to the supporting Web site, and cross into the WWSW by using a provided Web applet to run DOME and access the models. The ideas and knowledge within the models then become more widely and easily accessible to everyone, through commonly owned Web browsers.

3.4.2 Web site hosting of DOME applet

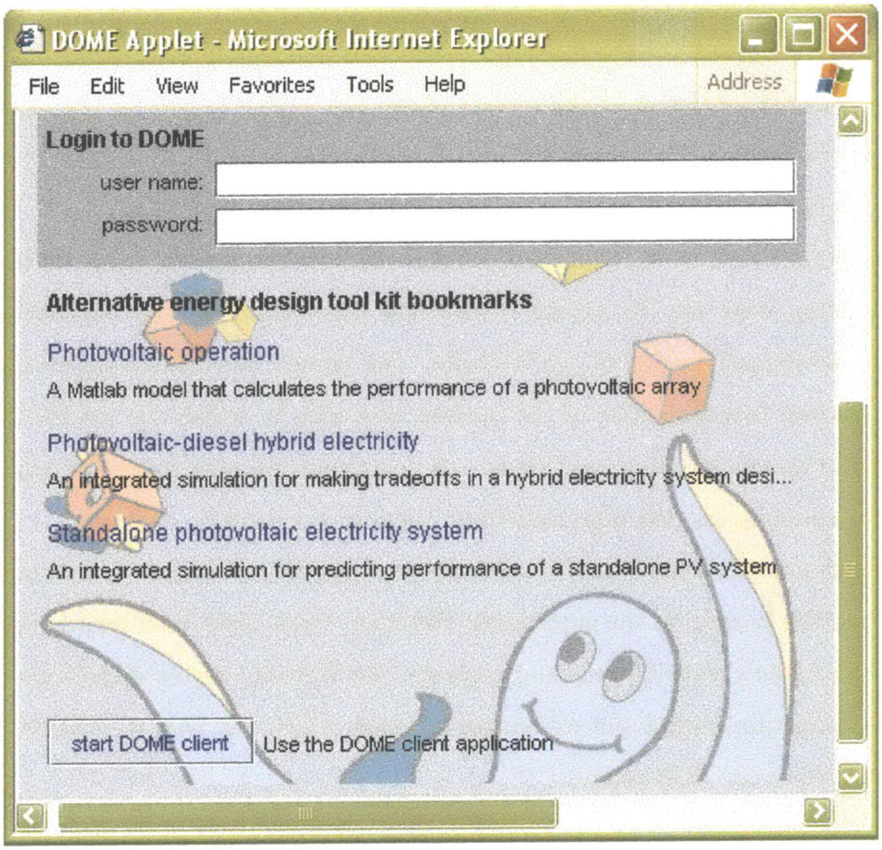
Continuing from the previous function as a bridge between the WWW and the WWSW, another function of the supporting Web site is a host for a DOME applet. The DOME applet, as discussed earlier, is an adaptation of the DOME application and is written as a Java applet[10].

---

[10] A Java applet is "a small Java program that can be embedded in an HTML page, and downloaded and executed by a Java-compatible web browser" [48].

Embedded in an HTML page in the DOME section of the supporting Web site, the DOME applet operates like a normal DOME application. Thus, it has a DOME run browser that is necessary for browsing the WWSW and locating models on different DOME servers. With this applet, anyone can use DOME and make use of the models in the toolkit without having to install the DOME application on their computers.

A snapshot of the DOME applet embedded in an HTML page is shown in figure 3-30. In the figure, a number of direct links, or bookmarks, can be seen. The bookmarks can lead a user conveniently to the models without having to browser through a number of DOME servers.



Alternative energy design tool kit bookmarks

Photovoltaic operation

A Matlab model that calculates the performance of a photovoltaic array

Photovoltaic-diesel hybrid electricity

An integrated simulation for making tradeoffs in a hybrid electricity system desi...

Standalone photovoltaic electricity system

An integrated simulation for predicting performance of a standalone PV system

Use the DOME client application

Figure 3-30: DOME applet embedded in an HTML page.

3.4.3 Model and idea transactions

The toolkit's supporting Web site serves another function as a center for models transactions, including contributions and requests of models. The models contributions, which are highly encouraged, can be done in two basic ways. In the first way, the developers can deploy their models directly to a reviewing space in the toolkit's central server. The newly submitted models will be reviewed before being moved to the toolkit's main space, where all the models are available to everyone. However, some developers may not want to share their models due to a proprietary reason, but may still want to share the functionalities of the models. These developers can choose to deploy the models on their own servers. After deploying the models, the developers can submit the models' descriptions and any related documentations, together with the network addresses of the servers where the models reside, to the model contribution section of the Web site. All users are able to access this section and discover what models have become available.

In addition to model contributions, models requests can also be made by the users through the supporting Web site. To request models, the users can post their requests on a Web board in the model request section of the Web site. The request should include detailed information, such as desired functionalities of the models, scenarios in which the models will be used for, and some other constraining conditions. All developers are able to see the requests, and those that have matching models may contribute them to the toolkit.

Other than models contributions and requests, general exchanges of ideas are also facilitated by several Web boards on the supporting Web site. With these Web boards, together with the sections for models contributions and requests, the Web site becomes the center for convenient models transactions and fluent exchanges of ideas, which can lead to different, interesting, or more creative design alternatives.

3.4.4 Information base

The toolkit's supporting Web site also functions as a base of information that is related to the fundamentals of the toolkit and renewable energy technologies in general. One important part of the information that the Web site provides is model documentation. Intended to give the users a better understanding of the models, the model documentation contains the models' brief overviews, relevant figures, as well as descriptions of parameters. For each parameter, a unit used and a valid range of input value are given. In addition, the model documentation also includes a list of all mathematical relations and available user interfaces of each model. With the list of the available interfaces, the users can choose to employ particular interfaces that are the most suitable for their usages[11]. Furthermore, the model documentation also provides information of the models' accuracy and limitation of usage, if asserted by the models' developers.

In addition to the model documentation, the Web site also provides sample integrated design scenarios, to demonstrate, step-by-step, how design simulations can be created using the models in the toolkits, and how an analysis can be incorporated into the simulations. Moreover, the Web site also makes available a number of papers that explain different underlying concepts and mechanisms of DOME, for those users that may be interested in more details about DOME. Lastly, the Web site also offers books references and links to other Web sites, where further information of renewable energy technologies can be obtained. By providing the information mentioned above, the supporting Web site helps expand the usability of the toolkit and proliferate the knowledge of renewable energy technologies.

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[11] See Section 2.2.3 Multiple forms of user interfaces.

Chapter 4

Solar energy models

The initial set of models in the Alternative Energy Design Toolkit is related to solar energy technologies. The models can be categorized as follow: PV system and components models, flat-panel collector models, economic analysis models, energy analysis models, solar radiation models, and other miscellaneous models. While details of all models are included in the model documentation of the supporting Web site, the following subsections discuss the models' overviews and important information.

4.1 PV system and components models

4.1.1 PV module operational characteristics

A PV module has three common characteristics: open-circuit voltage, short-circuit current, and maximum power. This model can be used to calculate these characteristics under different operating conditions, given the values at the standard condition[1].

Theoretically, a solar cell in a PV module can be considered as a circuit in figure 4-1. In the figure, the current I_l at the generator represents the light-induced current, and the diode represents the p-n junction of the solar cell. Under a short circuit, all the current passes through the external load and is equal to the light-generated current. This current is called short-circuit current. On the other hand, the open-circuit voltage is considered when the current I is zero,

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[1] The standard condition is defined as: incident solar irradiance at 1 $\mathrm{kW/m^2}$; spectral distribution at AM1.5, a typical spectrum on the Earth's surface on a clear day; and ambient temperature of 25 °C [29].

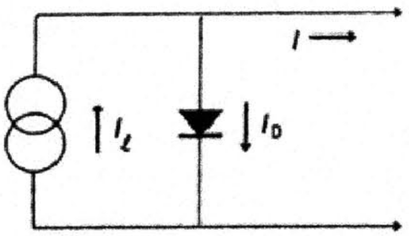

Figure 4-1: Equivalent circuit of a solar cell [29].

an open circuit [29]. Both the open-circuit voltage and the short-circuit current characterizes the I-V curve (shown in figure 4-2) of the solar cell. From the I-V curve, the power of the solar

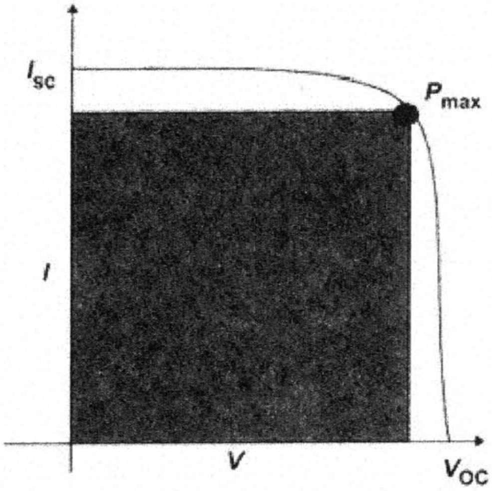

Figure 4-2: I-V characteristic curve of a solar cell [29].

cell operating at particular values of I and V can be determined from the area of the rectangle in figure 4-2. At both short-circuit ($I = I_{sc}$) and open-circuit ($V = V_{oc}$) conditions, no power is produced. The theoretical, maximum power ($P_{\max}$) can also be determined. Nonetheless, the maximum power can only be achieved in practice when a maximum-power-point tracker is equipped. The tracker is often used with large solar modules, but not with small or medium ones. For the small and medium modules, the voltage is usually set to be equal to that of the battery, and the theoretical, maximum power is seldom reached. Other than the three characteristics, this model also calculates the temperature of the solar cell and a fill factor for a module equipped with a maximum-power-point tracker. The fill factor is a factor that makes the product $I_{sc}V_{oc}$ equal to $P_{\max}$.

This model in the toolkit has two user interfaces: one for a PV module with a maximum-power-point tracker, and the other for a module without the tracker. In terms of the model's accuracy, the calculation of the fill factor assumes that the fill factor is constant throughout all operating conditions, even though it is a function of the irradiance and the cell's temperature. A derivation of the function is too complicated and impractical [29].

4.1.2 PV system load breakdown

This model, based on simple logics, is custom-developed for the toolkit. It can be used in a design of a PV power system, to calculate minimum rated power of the PV array and minimum capacity of the battery storage of the system. The underlying logics of this model can be explained as follow. For a given daily electricity load of the power system, daytime and nighttime portions of the load are determined from the number of hours of the day when there is solar irradiance for the PV array. Assuming that the nighttime load is satisfied by the battery, the amount of energy that the battery has to deliver is calculated, taking into account the battery's discharging efficiency. With the known amount of energy that the battery has to deliver, and a specified allowable minimum state-of-charge of the battery[2], the minimum capacity of the battery is then calculated.

In terms of the daytime load, it is assumed that the PV array can cover this load without needing help from the battery. While satisfying the daytime load, the PV array also has to charge the battery. The electricity needed to be delivered by the PV array is then equal to the summation of the daytime load and the energy required to charge the battery, taking into account the battery's charging efficiency. Lastly, once the total amount of the electricity delivered by the PV array is known, using the number of daytime hours, the minimum rated power of the PV can be determined.

This model has one straight forward interface. In terms of accuracy, this model relies on two main assumptions that the load can be considered constant during the day, and that solar

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[2] A minimum state-of-charge is set in order to prevent the battery from being overdischarged and to help prolong the battery's life.

irradiance is plenty enough for the PV to produce power at its rated value. The first assumption makes this model unsuitable for a design scenario in which the variation of the load during a day is significant. In other words, this model is more suitable for a design scenario whose time scope is so long that the load can be considered as a constant, such as a daily-average value, in a 24-hours period. Therefore, the model is still applicable to most of PV power systems designs, since the time scopes in the analysis of these design are almost always longer than a day.

4.1.3 PV array operation

This model simulates the complete operation of a PV array, and can be used as a component model in an integrated design simulation of a power system that utilizes a PV array. With given settings and properties of the array, conditions of the surroundings, and incident solar irradiance, the model can predict changes of the array's properties, thermodynamic attributes, instantaneous efficiency, and, most importantly, amount of electricity current produced.

To calculate the PV array's output current, the model first calculates the light-generated current, which is a direct effect of converting energy from the incident solar irradiance. Besides the solar irradiance, temperature of the solar cells and short-circuit coefficients, normally available from the manufacturer's specification sheet, also affect the light-generated current [39]. Once the light-generated current is determined, the PV array's reverse-saturation current is calculated next. The reverse-saturation current is a small current that flows back to the PV arrays at all time. It is a function of the solar cells' temperature and material properties. With the light-generated and reverse-saturation currents, the model can then determine the PV array's output current, by solving an implicit equation that involves the arrangement of PV modules in the array and the modules' properties.

The change in temperature of the solar cells in the array is resulted from the difference between the rates of incoming solar energy, departing heat losses, and generated power [45]. The rate of incoming solar energy is calculated from the incidence solar irradiance, the area of the array, and the solar cells' absorption coefficient. The heat losses comprise convective and radiative losses. The convective loss depends on difference between the ambient and solar cells' temperatures, and a heat transfer coefficient, which is a function of wind speed and the array's tilt angle [19]. Similarly, the radiative loss, to the ground and the sky, depends on the array's tilt angle, the ground's, the sky's, and the solar cells' temperatures, as well as the array's area. To determine the generated power, the last ingredient for calculating the temperature change, instantaneous conversion efficiency of the modules needs to be calculated. The instantaneous conversion efficiency also depends on the solar cells' temperatures. With the known efficiency, the instantaneous, generated power can be calculated. Lastly the solar cells' temperature change can be determined.

To achieve accurate predictions of the output current and the temperature change, all calculations discussed above need to be done in iterations of small time steps. This model is first implemented as a MATLAB script, in order to make use of its implicit equation solving ability, and later wrapped and made usable within the DOME context. The model has two user interfaces. One interface has a complete list of all input and output parameters. Users who have an access to detailed specifications of the array can use this interface to achieve the most accurate predictions. The other interface has a simpler list of input and output parameters. Most of the technical specifications are not exposed and set with default, commonly practiced values. This interface has a customized, graphical user interface, shown in figure 3-5.

The accuracy of this model is based on how precisely the model predicts the cell temperature. As mentioned earlier, the change in cell temperature is derived from an energy balance of the array over time. Therefore, the accuracy of this model can be improved by inputting real-time values to the model. For example, instead of an assumed, constant wind speed, a real-time value of the wind speed can be inputted at each time step. Moreover, the formula used to calculate the convective heat transfer coefficient of the array [19] is only applicable for a tilt angle of less than 25 degree and with a low to moderate wind speed. Nonetheless, even with this constraint, the model is still applicable to most design scenarios

4.1.4 PV system controller operation

This model simulates an operation of a controller in a PV power system. The main function of the controller is to manage the flow of energy, or electric current, between components of the system. (See figure 4-3). In managing the current flow, the controller denotes the status of the system with three indicators: FCM, BCM, and LVD. FCM (Float Charge Mode) denotes the system when the battery is in a normal working condition, as it is being constantly charged and

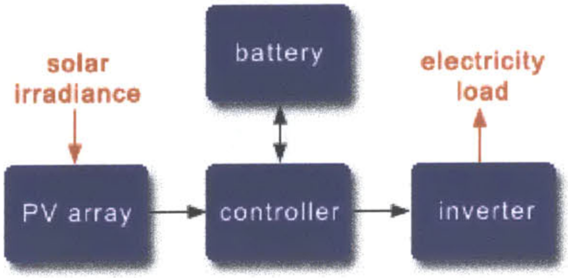

Figure 4-3: Energy/current flow in a PV power system.

discharged and its voltage floats between the *minimum-floating-voltage* and *maximum-floating-voltage* levels. Sample values of these voltage levels of a system with a 24-V battery are shown in table 4.1.

battery levels	*value*
boost voltage	28.8
maximum float voltage	27.8
reconnect voltage	26.8
minimum float voltage	25.2
disconnect voltage	22.6

Table 4.1: Example voltage levels settings for a PV power system with a 24-V battery.

When the battery is discharged more than it is charged, and its voltage drops below the minimum-floating-voltage level, BCM (Boost Charge Mode) is engaged by the controller. In BCM, the battery is boost-charged, and stays in this mode until the voltage reaches the *boost voltage* level, after which further charging of the battery is prevented. When the battery voltage drops down to less than the minimum-floating-voltage level, the controller shifts the system into FCM. Note that BCM and FCM are always mutually exclusive, except when the voltage is over the boost level.

To prevent over-discharging of the battery, the controller activates LVD (Low Voltage Disconnect) when the battery's voltage drops below the *disconnect voltage* level. With LVD activated, the controller stops the electricity delivery to the load, allowing the battery's voltage to only rise. Normally, when LVD is activated, the system is also engaged in BCM. The load is kept disconnected unless the battery's voltage rises back to above the *reconnect voltage*, when LVD is deactivated. Note that while BCM and FCM are related, LVD is not. BCM and FCM signify the charging/discharging of the battery, but LVD signifies the electricity delivery to the load.

The determination of the system status is done after every time instant. In addition to the battery's voltage, system status from the preceding time instant is also used by the controller to determine the system status of the next time instant. Then, depending on the new system status, the controller instantaneously determines how much current should be charged to, or discharged from, the battery.

This model is custom-developed for the toolkit, based on basic ideas of a controller's operation [45].

4.1.5 Lead-acid battery operation

This model, based on publications by [15] and [6], represents a dynamic behavior of a lead-acid battery, which is used in photovoltaic systems. Taking into account the fact that the battery's capacity depends on the charge/discharge rate's history, the model predicts the battery's output voltage and state-of-charge (SOC). The SOC represents electric charge stored by the battery at a given time, normally with a unit of Wh (Watt-hour). For any battery, its maximum SOC is a product of the battery's nominal voltage and capacity. SOC is more commonly used in a form of a normalized value, with respect to the maximum SOC.

The battery's SOC and open-circuit voltage are closely related. The open-circuit voltage represents the amount of energy stored in the battery, and its instantaneous value is a function of the instantaneous SOC and whether the battery is being charged or discharged. For a given SOC at the starting time, the model first determines a corresponding open-circuit voltage. Using the open-circuit voltage's value, together with the amount of electric current being charged/discharged and some battery's properties[3], the model can predict the SOC of a succeeding time instant, which is only a very small time period after the previous one. Then, the new SOC is used to determine the open-circuit voltage of the new time instant, and the model again predicts the SOC of the following time instant. The process is iterated until the specified time instant is reached, at which the final SOC is determined. Next, the SOC is used,

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[3] The battery's properties used in this calculation include the self-discharging rate and the charge/discharge efficiency.

again for one last time, to determine the open-circuit voltage, as well as the battery resistance. Both values are calculated differently depending on whether the battery is being charged or discharged. Lastly, the model calculates the battery's output voltage based on the open-circuit voltage and resistance.

With the calculations discussed above, this model can determine the changes in the battery's output voltage and SOC, after an amount of electric current has been charged to, or discharged form, the battery for a specified period of time. However, this model is a simplified version that only accounts for charging and discharging modes of the battery, and might not accurately simulate the over-charge and over-discharge periods. Nonetheless, even without the simulations of the over-charge/discharge periods, the model still provides good predictions in general, and the computation is relatively much faster.

4.1.6 Inverter operation

An inverter is a DC (direct current) to AC (alternating current) converter. It is commonly used in a PV power system, in order to convert DC, generated by the system, to AC before delivering it to the load. For a specified output power to deliver to the load, this model can determine the input power and current required.

For any inverter, a given amount of electrical power going into it always comes out less, due to a number of losses. Some of the power losses are fixed, including those from the core transformer and the switching board. The other power losses are variable, resulted from resistances of the transformer's copper and the load. This model first calculates these losses and then determines the amount of input power required to deliver a specified output power to the load. Lastly, the amount of required input current is determined from the calculated input power and a given terminal voltage.

The model has two interfaces. The first interface is suitable for a design whose detailed information of the inverter's losses and resistance are known, including the losses at the core transformer and switching circuit, and the resistances of the load and transformer's copper. The second interface is suitable for when the transformer's loss coefficients are available from a manufacturer's specification sheet, since the inputs required for this interface are fixed and variable loss coefficients, instead of detailed power losses. The basics of this model are obtained from a publication by [45].

4.2 Flat-panel collector models

4.2.1 Top heat loss of a flat-panel collector

In order to determine the thermal efficiency of a solar collector, it is important to first find out the collector's heat loss coefficient [17]. This model can be used to calculate a flat-panel collector's top heat loss, which is due to convection and radiation. A schematic diagram of a solar collector is shown in figure 4-4.

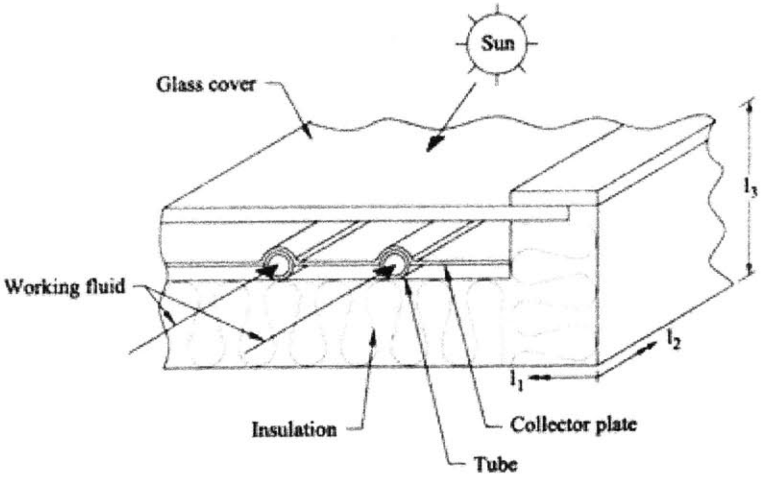

Figure 4-4: Schematic diagram of a solar collector [17].

The model starts with a calculation of a wind heat transfer coefficient, by using an equation proposed by [17]. The equation states that the wind heat transfer coefficient is a linear function of the wind speed. Once the wind heat transfer coefficient is obtained, the model can calculate the collector's top loss coefficient. To accurately assess the top loss coefficient, an iterative thermal network analysis is required. However, this type of analysis is complicated and consumes a lot of time. An alternative and simple function is proposed by [1]. This function takes into account both convective and radiative losses, and requires a number of input parameters, including the absorbing plate's temperature and emissivity, the number of covers and their emissivity, the collector's tilt angle, and the ambient temperature. Finally, taking into account the absorbing plate's area and the temperature difference between the plate and the ambient, the model calculates the total heat loss from the top of the collector.

In terms of accuracy, the simplified function for determining the collector's top loss coefficient produces results with good agreement with those of the iterative analysis. Nonetheless the good agreement in results is only guaranteed under the following conditions:

absorbing plate's temperature	320 - 420 K
absorbing plate's emissivity	0.1 - 0.95
ambient temperature	260 - 310 K
number of covers	1- 3
wind speed	1 - 10 m/s
wind heat transfer coefficient	less than 40 W/m^{2}K

Even with the limited ranges of applications, this model is still applicable to most design situations. Plus, the fast and simple computation makes it much more practical than the accurate, but complicated, iterative thermal network analysis.

4.2.2 Efficiency of a flat-panel collector

Continuing from the previous model, this model determines several efficiencies of a flat-panel solar collector, as well as its useful heat transfer rate. The model takes into account the geometries of the collector, its operating condition, and the working fluid's properties.

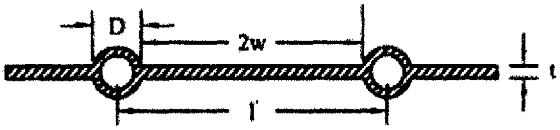

Figure 4-5: An absorbing plate as a fin connecting two adjacent channels.

As seen in figure 4-5, an absorbing plate connecting two adjacent, working-fluid channels acts as a fin for transferring heat to the channels, and hence to the working fluid. This model can determine the collector's *fin efficiency*, which is a ratio of the actual rate of heat flow through the fin and the maximum possible rate of heat flow [17]. The fin efficiency is based on the geometries of the fin and the channel, the plate's thermal conductivity, and the collector's overall conductance, which accounts for the effects of radiation and convection between the plates, radiation and convection between the cover and the ambient air, and conduction through the insulation [17].

Other than the fin efficiency, the model can also determine the *collector efficiency factor*, which is a ratio of thermal resistance between the collector and the ambient air, and thermal resistance between the working fluid and the environment. The collector efficiency factor can be considered as a design parameter. It depends on the collector's overall conductance, the fluid heat transfer coefficient, the fin efficiency, and slightly on temperature.

In addition, the model can determine another characteristic of the collector, called the *heat-removal factor*. Used to compare the performance of a real collector with a thermodynamic optimum, this factor is a ratio of the actual rate of heat transfer to the working fluid to the rate of heat transfer at minimum temperature difference between the plate and the environment [17]. The heat-removal factor increases with the working fluid's flow rate, with the collector efficiency factor as an upper limit.

Once the heat-removal factor is determined, the model can calculate the *useful heat transfer rate* of the collector. The useful heat transfer rate is also a function of many other variables, including the collector's area, the cover's transmittance, the plate's absorptance, the solar irradiance, the collector's overall conductance, and the temperature difference between the inlet fluid and the ambient. Lastly, the model can use the useful heat transfer rate to calculate the *collector's instantaneous efficiency.*

This model is based on a number of equations in a publication by [17]. The derivations of the equations are simplified with the following assumptions:

- The collector is thermally in steady state.
- The temperature drop between the top and bottom of the absorbing plate is negligible.
- Heat flow through the cover and the insulation is one-dimensional.
- The flow through the tubes is uniform.
- The sky is equivalent to a black-body source for infrared radiation.
- The solar irradiance on the collector is uniform.

4.3 Economic analysis models

4.3.1 PV system life-cycle costing

One way to assess the economic value of a PV system is to calculate its life-cycle costing. The life-cycle cost is the sum of all costs of the system throughout its lifetime, expressed in today's money. The life-cycle cost of a PV system consists of four main costs: capital, installation, annual operation and maintenance (O&M), and recurring component-replacement costs. An approximate value of each individual cost, as a guideline, is provided by literature reviews, summarized by [36]. The cost estimates are in a form of cost per unit power, such as dollar per Watt. In light of this model, an estimate of the electricity cost of a PV system can be made and compared with other methods of electricity generation.

The system's capital cost consists of costs of the PV modules, power conditioner, supporting structure, and battery storage. To calculate the capital cost, this model requires a number of inputs, including the PV array's rated power; the battery's rated capacity; the costs of the modules, the conditioner, and the structure per unit power of the array; and the cost per unit capacity of the battery. As mentioned earlier, the estimates of the costs per unit power, or capacity, are statistically based on data from literature reviews and are included as a guideline for the users. For example, the cost estimate is \$3.74 per Watt for the PV modules, and \$175 per kilowatt-hour for the battery.

The system's installation and annual O&M costs are harder to assess than the capital cost. Nonetheless, they can be estimated as fractions of the capital cost [36]. The literature reviews suggest that the annual O&M cost is about 2% of the capital cost, while the installation cost can vary from 18% to 50%. While the installation cost is a one-time cost, the annual O&M cost recurs every year throughout the system's life-cycle. Thus, the O&M cost has to be adjusted, by multiplying an annualization factor. The annualization factor is used to calculate the *present worth*[4] of a payment occurring annually, and is based on a discount rate and an excess inflation[5] [29].

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[4] The present worth is an equivalent value of a future cost or payment in today's economy.

[5] For example, in a period of 20 years, with 10% discount rate and 5% excess inflation, the annualization factor is 12.72. With this annualization factor, if the annual cost of a component is \$50 per year, the present worth of cumulative cost over 20 years is 12.72 x \$50 = \$636.

The last type of cost that constitutes to the system's life-cycle cost is the recurring component-replacement cost. Like the O&M cost, the recurring component cost has to be adjusted to the present worth. The adjustment is done by multiplying the cost with the discount factor. The discount factor is used to calculate the present worth of a payment to be made in a specified number of years from the present[6]. This model takes into account the present worth of all components' recurring costs. After that, the model can determine the system's life-cycle cost by summing up all the fixed and recurring costs. The model can also determine the annualized life-cycle cost, taking into account the discount rate and excess inflation. Lastly, the cost of the electricity generated by the system can be calculated, by dividing the annualized life-cycle cost with the amount of the annually generated electricity.

The accuracy of this model depends on the estimates of costs per power input by the users. While the suggested statistical cost estimates are quite reliable, they are based on literature surveys that may include outdated data. Nonetheless, the users always have a freedom to use any values that seem more reasonable. In addition, the model also relies on the assumptions that the discount rate is constant throughout the system's lifetime, and that the cost of the inverter is included in that of the power conditioner.

4.3.2 Engine-generator system life-cycle costing

Similar to the previous model, this model assesses the economic value of an engine-generator system by calculating its life-cycle costing. Unlike that of a PV system, the life-cycle cost of an engine-generator system consists of five main costs: capital, installation, annual operation and maintenance (O&M), recurring component-replacement, and annual fuel consumption costs. The annual fuel consumption has a significant influence on the difference between the life-cycle costs of the PV and engine-generator systems in a long run.

The capital cost consists of costs of the engine-generator and the fuel storage. Three types of engine-generators are considered in this model, namely, gasoline, 3000-rpm diesel, and 1500-rpm diesel engines. For each type of engine, the model provides a formula to calculate the cost per unit rated power of the engine. The formulae, statistically based on data from literature

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[6] For example, in a period of 10 years, with 10% discount rate and 0% excess inflation, the discount factor is 0.39. With this discount factor, a component that presently costs $1000 has a present worth of $390 when the payment is made 10 years from now.

reviews, are proposed by [36]. In addition, the rated power of the generator, the size of the fuel storage, and the cost of the fuel storage per unit size are also required to calculate the capital cost. A sample value of the cost of the fuel storage per unit size is also provided [32].

The installation cost is considered as a fraction of the capital cost, in a similar fashion to the previous model. However, the O&M cost of the engine-generator system is more complicated to calculate. The O&M cost includes the costs of oil change, air-filter cleaning, and replacements of the oil-filter, air-filter, fuel-filter, and spark plugs. Each of the activities has a different period. For example, the oil change period is every 100 hours for the gasoline engine, but it is every 150 hours of operation for the 1500-rpm diesel engine. The other activities occur after specific numbers of oil changes [32], as shown in table 4.2. The costs of these activities are averaged to obtain the annual O&M cost. Since the annual O&M cost recurs throughout the system's lifetime, it has to be adjusted with the annualization factor, in order to find the present worth of the total O&M cost.

activities	*period (number of oil changes)*
air-filter cleaning	1
oil-filter replacement	2
air-filter replacement	4
fuel-filter replacement	4
spark plugs replacement	4

Table 4.2: Periods of activities related to the operation and maintenance of an engine-generator power system.

Next the recurring component-replacement cost is calculated in a similar way to the previous model. The only difference is that, the lifetime of the engine-generator is specified as a number of hours of operation[7]. Unlike a PV module that has a lifetime of about 20 years, the engine-generator may only last for less than 5 months if it operates for 24 hours a day. Again, each recurring component-replacement cost has to be adjusted to the present worth by using the discount factor.

The last type of cost is the fuel consumption cost. The fuel consumption rate, in fuel volume per unit electricity generated, of the engine-generator is a function of its rated and operating powers. Functions for estimating the fuel consumption rates of the diesel and gasoline

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[7] The lifetimes of gasoline, 3000-rpm diesel, and 1500-rpm diesel engine-generators are 3500, 6000, and 10000 hours, respectively.

engine-generators are also provided [32]. Once the fuel consumption rate is obtained, the model can calculate the annual fuel consumption cost from the amount of electricity generated annually and the fuel cost per volume. Then, the life-cycle fuel cost can be obtained using the annualization factor. Finally, after all costs are calculated, the life-cycle cost of the system can be obtained, as well as the annualized life-cycle and electricity costs.

In terms of accuracy, this model also assumes that the discount factor is constant throughout the system's lifetime. In addition, it also assumes that the electricity generated by the system will be delivered directly to the loads, either as a standalone system or as a backup for a PV system. In a case where the electricity is used to charge a battery, this model has to be modified to account for an inverter required for the system.

4.4 Energy analysis models

4.4.1 PV module life-cycle energy analysis

This model is based on a work in [24], where a life-cycle energy analysis (LCEA) is applied to a photovoltaic module design. LCEA, a component of life-cycle inventory (LCI), measures the energy inputs and outputs of a product's life-cycle. The life-cycle of a photovoltaic module starts from the material production, manufacturing, use, to end-of-use management. As results of the analysis, three measures of the system's performance are presented: energy payback time, electricity production efficiency, and life-cycle conversion efficiency. These three measures can be used in an early stage of a PV system design to compare performance of different types of solar, as well as other, electricity-generating technologies.

The *material production energy* is the total energy required to produce the materials that are used in the module. To determine the module's material production energy, the model has to take into account the amount of each material used in the system, as well as the specific energy required in production of the material. Usually, the actual amount of the material consumed is higher than the amount that is present in the final module, since some of the material is lost in forms of wastes or scraps. Example values of the specific material production mass and energy, obtained from [23], are provided as a guideline for the users in tables 4.3 and 4.4.

The next type of energy considered is the *manufacturing energy*, which is the total energy

material	*mass (t)*
aluminum:	
PV array	2.0
silicon:	
PV array	1.1
copper:	
PV array	0.3
stand	5.0
inverter	0.3
insulating material:	
PV array	1.5
stand	3.0
inverter	0.2
glass:	
PV array	6.0
iron / steel:	
stand	7.5
inverter	0.5

Table 4.3: Production weights of the materials used in a poly-Si PV module (rated output 100 kW).

material	*production energy consumption rate (kWh/kg)*
aluminum	61.402
silicon	654.070
copper	12.745
insulating material	28.708
glass	4.360
iron / steel	7.203

Table 4.4: Energy consumption rate in productions of the materials used in the module.

required to manufacture the module. The manufacturing energy includes the energy invested in the process fuel, productions of process materials, manufacturing facilities, production and maintenance of manufacturing equipments, human labor, administrative services, and research and development. Some of these components are quite arbitrary and insignificant. sample data of energy consumed in different steps in the production of a 22-W PV module [24] is shown in table 4.5.

process step	*equivalent primary energy (MJ)*
encapsulation	56.2
amorphous Si alloy deposition	37.9
transparent Conductive Oxide (TOC) deposition	32.7
Back reflector deposition	30.3
aluminum extruding process	26.0
substrate wash	23.1
TOC etch	7.0
short passivation	7.0
grid pattern screen print	7.0
testing and packaging	negligible

Table 4.5: Example of manufacturing energy consumed in different steps in the production of a 22-W PV module.

In addition, the model also needs to consider the *use energy*, which is the energy consumed by the module during the use phase. The use energy includes the energy invested in the installation and the annual O&M of the module. The operation energy is zero for most PV module, except those that have a tracking system. Also, the maintenance energy is usually very low. Furthermore, the *distribution* and *end-of-life management energy*[8] are also considered. Both of these are also less significant, compared to the material production and manufacturing energy. Once all the energy discussed above is determined, the model can calculate the total life-cycle energy input to the module.

Next, the system's life-cycle energy output needs to be considered. This energy is equal to the total energy generated by the module, in this case, in form of electricity, minus any energy losses at the module's power conditioner. After both life-cycle input and output energies of the module are obtained, the model can calculate the three measures of the module's performance. First, the *energy payback time* is calculated, based on the total input energy and the power

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[8] For shredding in hammer mills, the energy required is about 97 J/kg [21].

generated by the module. The energy payback time is the time required to recover the total energy invested in the PV module.

Second, the module's *electricity production efficiency* is determined, simply as a ratio between the input and output energies. This value is useful for comparing competing electricity-generating systems. For many PV modules, this value is higher than unity, meaning that the electrical energy produced during the module's lifetime is greater than the total energy invested in the module. This kind of high efficiency can not be achieved by fossil-fuel electricity-generating systems. For example, the US electricity grid has an electricity production efficiency of only 0.32. Finally, the *life-cycle conversion efficiency* is determined. It is defined as a ratio of the net productivity of the PV module[9] to the total solar input energy. This value is a useful assessment for comparing different solar power technology systems.

In terms of accuracy, some of the inputs to this model need to be estimated. Thus, the results from the model cannot be considered completely accurate. Nonetheless, this model characterizes a PV module more realistically than any of the previous studies, by also taking into account the energy consumed in the system's end-of-life management. More importantly, this model offers several measures of the system's performance, so that a number of different designs can be assessed and compared.

4.4.2 Simplified PV module and battery energy analysis

This model is derived from the previous model and is different from it in many ways. First, the period of the analysis is not limited to just the module's lifetime. Second, the input and output energies of the system are entered explicitly to this model, making it suitable for the designs in which a specific amount of output energy is required from the system. Third, a battery is considered as part of the system, as the energy associated with the battery's manufacturing is added to this analysis. Therefore, while the previous model can only be applied to a PV module, this model can be used to assess the energy-wise performance of a whole PV power system.

In addition, this model requires much simpler inputs than the original one does. Specifically, to determine the PV module's material production energy, the users only need to enter the rated

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[9] The net productivity is the difference between the input and ouput energies.

power of the PV modules. The model then automatically normalizes that value with a literature value, whose amounts of production materials and their specific production energies are known. Thus, the users can obtain the material production energy of the PV module in the system with just one simple input. Furthermore, the calculation of the module's manufacturing energy is also done in a similar fashion. Namely, the users can determine the module's manufacturing energy by inputting only the module's rated power.

With another key difference in this model that allows the period of analysis to be longer than the module's lifetime, the replacements of the PV module have to be taken into account. In doing so, the model first calculates the number of times of installations, including the first installation and succeeding reinstallations, based on the given module's lifetime and analysis period. Next, several energies that constitute the system's input energy have to be multiplied by the number of installations. These energies include the material production, manufacturing, installation, and distribution energies. Similarly, the end-of-life management energy has to be multiplied by the number of installations minus one[10]. In addition to the energies related to the PV module, the energy required to manufacture the battery is also included in the system's input energy. A formula for estimating the battery-related energy is provided [23]. Once all of the energies mentioned above are determined, the PV system's total input energy over the entire analysis period can be calculated.

Unlike the previous model, this model does not need to calculate the system's output energy, since it is specified as a target by the users. With the system's total input and output energies, in a similar way to the original model, this model can determine the system's electricity production efficiency and energy payback time, as measures of the system's performance.

While requiring only simple inputs from the users and making the analysis easy, this model might not be completely accurate. This is because some calculations, such as those of the energies related to the PV module's material production and manufacturing and the battery's manufacturing, are only based on the normalizations with statistical values from literatures. However, with its flexibility in terms of the analysis period and its coverage of the entire PV power system, this model is still suitable for a fast estimate of the system's energy.

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[10] This is because the end-of-life management energy is not associated with the first installation.

4.4.3 Simplified diesel generator energy analysis

Much similar to the previous model in terms of simplicity and applications, this model uses the concepts of electricity production efficiency and energy payback time to evaluate the energy-wise performance of diesel generator systems. As mentioned before, the two performance indicators are based on the total input and output energies of the system. Like in the previous model, the period of analysis in this model can be longer than the generator's lifetime. Also, the system's output energy is entered explicitly by the users.

Similar to the previous model, the generator's installations, including the first installation and succeeding reinstallations, during the analysis period are also considered in this model. Consequently, to be included in the system's total input energy, the manufacturing, installation, O&M, and distribution energies have to be multiplied by the number of installations. Also, as part of the total input energy, the system's end-of-life management energy needs to be multiplied by the number of the installations minus one.

The last component of the total input energy is due to the diesel fuel consumption by the generator. To account for this energy, the model first determines the fuel consumption rate of the generator, using a formula proposed by [32]. The fuel consumption rate is a function of the generator's rated and operating powers. Once the fuel consumption rate is obtained, it can be used, together with the fuel's heating value and the system's output energy, to calculate the system's energy input due to the fuel. Lastly, the system's total input energy can be calculated and used to find the electricity production efficiency and energy payback time. Like the previous model, this model requires only simple inputs from the users and is suitable for a quick assessment of the system's energy.

4.5 Solar radiation models

4.5.1 Sun-earth geometric relationship

This model analyzes several geometric relationships between the sun and the earth, and determines the sun's position at any specified time and location. Important attributes of the sun's position include the altitude, declination, and azimuth. In addition, several related information, such as times of sunrise and sunset, can also be calculated. These values are often necessary for determining the amount of solar radiation available at a certain site through some certain time.

In the aspect of the sun's position, the model starts with a calculation of the *solar declination*, which is an angle between the earth-sun line and the plane through the equator, as denoted as δ_s in figure 4-6. The solar declination's "tilt" is the major cause of a seasonal variation in the availability of solar radiation. The solar declination varies from -23.45° at winter solstice (December 21^{st}) to 23.45° at summer solstice (June 21^{st}). The value is at 0° at fall and spring equinoxes (September $21^{st}$and March 21^{st}, respectively). See figures 4-7 and 4-8. The solar declination is independent of the observer's position on the earth. In fact, it is a function of the day number[11] of the year only.

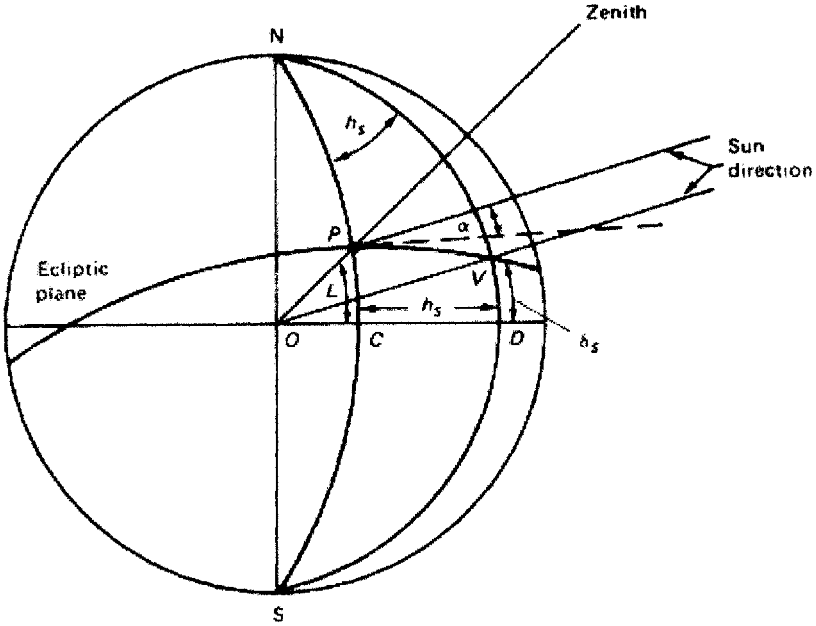

Figure 4-6: Illustrations of a site's location P, its latitude L, solar declination δ_s, solar altitude α, and solar-hour angle h_s [17].

To determine other attributes of the sun's position, the time of the day needs to be specified. In most calculations, it is more convenient to translate the local standard time into the *solar time*, which is the time of the 24-hour standard, based on the nominal 360° that the sun travels

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[11] The day number is starts at 1 on January 1 of every year.

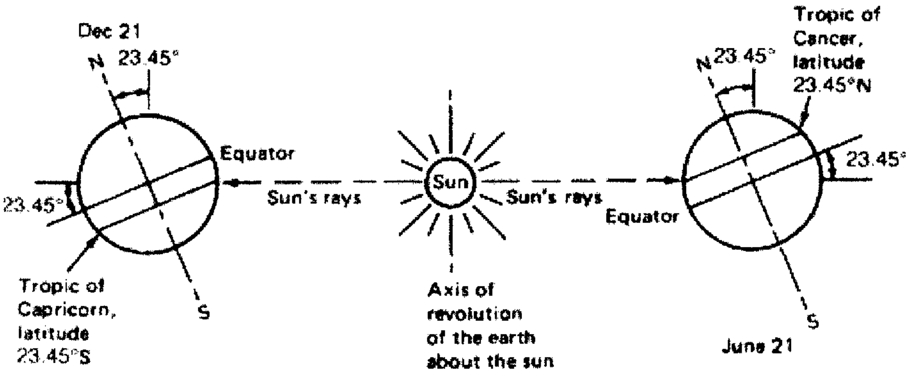

Figure 4-7: Positions and angles of the earth to the sun, for the winter solstice (Dec 21) [17].

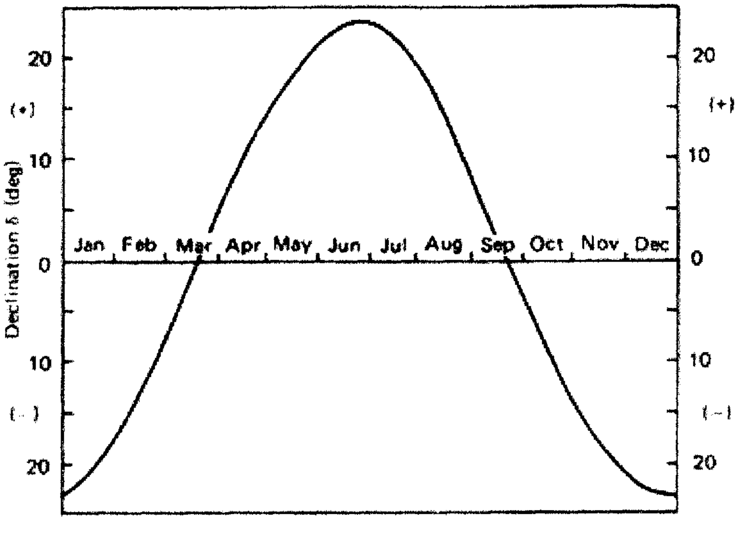

Figure 4-8: Solar declination through out the year [17].

around the earth in 24 hours. The solar time usually differs from the local standard time because of the irregularity of speed of the earth's motion around the sun. The model can determine the solar time for a particular site, using the site's latitude, local standard time, and standard time meridian of the time zone in which the site locates. With the solar time determined, the model can then calculate the *solar altitude* angle for a given site at a given time. By definition, the solar altitude is an angle between the line collinear with the sun's rays and the horizontal plane, as shown in figures 4-6 and 4-9. The solar altitude can range from -90° to 90°; although practically, at a lower solar elevation, the center of the sun appears on the horizon when it is actually 34′ below the horizon[12]. Since the sun has a radius of 16′, the sun can be visible when the solar altitude angle is as low as -50′.

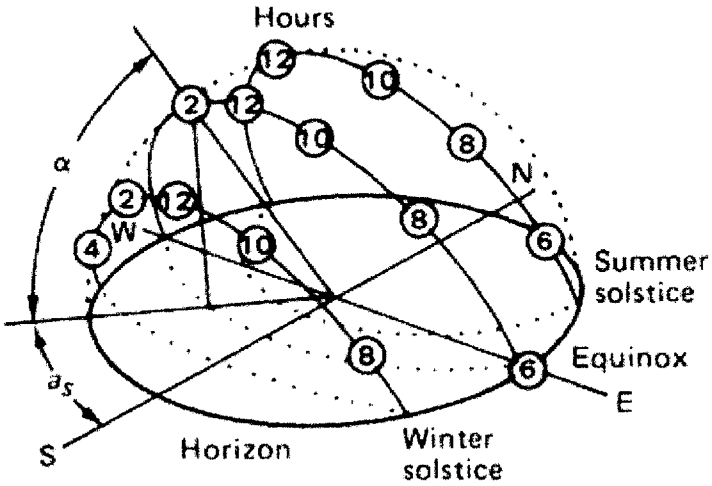

Figure 4-9: Sun paths for the summer and winter solstice, and the autumn and spring equinoxes, shown with numbers signifying the hours of the day [17].

After the solar altitude is determined, the model can then calculate the *solar azimuth* angle of the same site and time. The solar azimuth is an angle between the due south line and the projection of the line connecting the sun to the site on the horizontal plane. Since the azimuth angle is resulted from an arcsine calculation, its value as a result of most computer program is usually limited to the range from -90° to 90°. However, the actual value can range from -180° to 180° (with 0° and 180° at the due-south and due-north lines, respectively). Specifically, the

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[12] 60′ is equal to 1°.

value is beyond the [-90°, 90°] range when the sun is north of the east-west line, which can happens in two scenarios:

1. at a location whose latitude is lower than the solar declination on that day, and
2. at a location whose latitude is higher than the solar declination on that day, and at the solar time before the due-east time or after the due-west time[13].

   To address this issue, the model uses several equations, provided for different conditions and each one with an appropriate angle correction.

Other than the solar declination, solar altitude, and solar azimuth, the model can calculate other related information, including the solar due-east and due-west times, as well as the times of sunrise and sunset. In terms of the user interfaces, this model provides seven different interfaces, tailored for different uses, as listed below.

- Solar time Interface, for translating the local standard time to the solar time
- Local standard time Interface, for translating the solar time to the local standard time
- Solar declination Interface
- Solar due east and west times Interface
- Sunrise-sunset solar times Interface, for determining the sunrise and sunset times in the solar time standard
- Sunrise-sunset local standard times Interface, for determining the sunrise and sunset times in the local time standard
- Complete solar-time-based Interface, for determining all of the sun position's attributes, including the solar declination, solar altitude, and solar azimuth, as well as the solar due-east, due-west, sunrise, and sunset times.

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[13] The solar due-east and due-west times are the solar times when the sun crosses the east-west line before and after noon, respectively.

4.5.2 Extraterrestrial radiation

This model compares three different estimates of the extraterrestrial radiation on a given day. The extraterrestrial radiation is the incident solar radiant energy flux on the earth's atmosphere, per unit area normal to the sun's direction. This value varies throughout the year due to the elliptical orbit of the earth.

A complete equation for determining the extraterrestrial radiation requires input values of the sun-earth distance, the annual-average sun-earth distance, and the solar constant, which is an extraterrestrial radiation measured at the mean sun-earth distance[14]. In other words, the complete equation can determine the extraterrestrial radiation for a given sun-earth distance. Since this approach is impractical, and the sun-earth distance can be related to a day number, several publications propose simplified equations to estimate the extraterrestrial radiation as functions of the day number. This model include three equations proposed in [11], [17], and [44]. While the results from these estimates may be slightly less accurate than the original equation, they are much more practical and easy to use.

4.5.3 Solar radiation on a tilted surface

Solar radiation on any surface is a combination of beam, diffuse, and ground-reflected radiations. This model calculates those three component radiations on a tilted surface. As the first step of the calculation, the model has to determine the *incident angle*, which is an angle between the line normal to the surface and the line collinear with the sun's rays. (See figure 4-10). The model calculates the incident angle, using a trigonometric relation between the solar altitude angle, the solar azimuth angle, and the tilted surface's azimuth angle.

In order to determine the beam, diffuse, and ground-reflected radiations on the tilted surface, the model needs to calculate those radiations on the earth's surface first. The *beam radiation* on the earth's surface is essentially the extraterrestrial radiation that is attenuated after traveling through the atmosphere but still maintains its direction. The beam radiation is a function of the clearness number and the atmospheric optical depth. The values measure the clearness of

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[14] The solar constant indicated by NASA is 1353 W/m2 (±1.6%). Fröhlich et al. revised this number to 1377 W/m^2. Currently there is no consensus on the value of the constant, although, the value of 1367 W/m^2 is presented in many references [17].

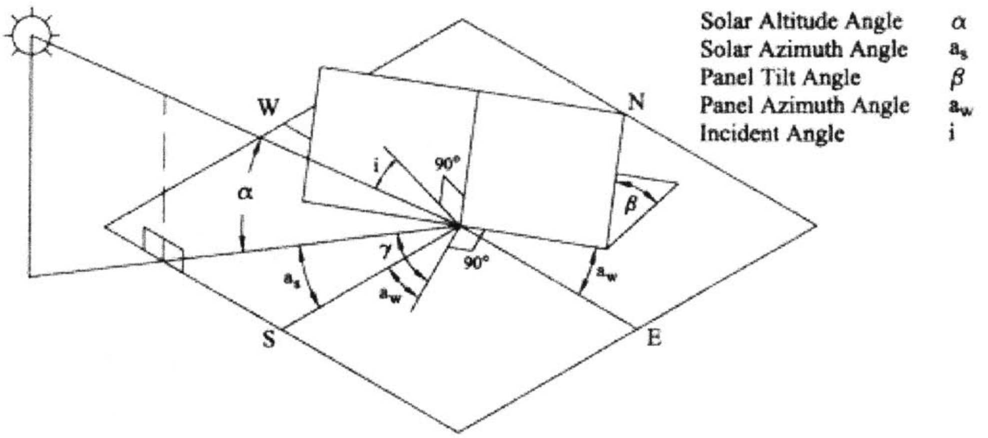

Figure 4-10: Angles used in calculations of solar radiation on a tilted surface [17].

the sky and the condition of the atmosphere, respectively. Even though the clearness number can be easily estimated[15], data for the atmospheric optical depth is available only for limited locations. Other than the beam radiation, the model also determines the *diffuse radiation*, which is the scattered solar radiation that reaches the earth's surface. The diffusion radiation can be calculated by multiplying the beam radiation with the sky diffusion factor, which is a coefficient that indicates the radiation in the sky is scattered and reaches the earth's surface afterward. Unfortunately, like the atmospheric optical depth, data for the sky diffusion factor is available only for limited locations. With the beam and diffuse radiations on the earth's surface, the model can calculate those radiations on the tilted surface by using simple trigonometric equations.

In addition, the *ground-reflected radiation* on the tilted surface can be calculated, based on the beam radiation, the panel's azimuth angle, the solar altitude angle, and the ground reflectance[16]. Finally, the model then determines the total radiation on the tilted surface, by combining the beam, diffuse, and ground-reflected radiations.

This model has two interfaces: one that provides the complete results, and the other that only deals with the incident angle. Although simple and easy to understand, this model can only be applied to limited locations, whose data for the atmospheric optical depth and the sky

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[15] The clearness number has a range between 0 and 1. It is usually set as 1 for a clear sky [49].

[16] Approximated values for normal and snow covered grounds are 0.2 and 0.8, respectively [17].

diffusion factor is available.

4.5.4 Global irradiance on inclined surface

This model has the same purpose as that of the previous model, but uses a totally different approach. Namely, this model, based on a work in [37], does not require the information of direct, diffuse, and ground-reflected radiations, which often depend on a lot more parameters, such as the atmospheric states, properties of the adjacent surfaces, topology, and geometric factor. In contrast, this model requires only the sun's position and the horizontal global irradiance as inputs. By definition, the horizontal global irradiance is the total irradiance on a horizontal surface. Since the horizontal global irradiance is available at all meteorological stations, this model is more widely applicable than the previous model. Also, satellite-derived global irradiance data can be used in place of the horizontal global irradiance in this model.

To calculate the horizontal global irradiance, the model first needs to determine the incident angle, in an exact same way as in the previous model. Once the incident angle is known, the global irradiance on the tilted surface can be calculated based on the known horizontal global irradiance, the zenith angle, and the clearness index. The clearness index is a ratio of the global horizontal irradiance to the extraterrestrial horizontal irradiance. Simply put, it is a measure of the clearness of the sky and its value, ranging from 0 to 1, can be easily estimated. In addition, the model can take into account the radiation due to anisotropic reflections. In doing so, the model first calculates the anisotropic factor, which is a simple function of the incident angle and the ground reflectance[17]. Lastly, after the anisotropic factor is obtained, the model can use it to calculate the total global irradiance on the tilted surface.

In terms of accuracy, the developers of the work used in this model [37] claim that the results from this work agree well with experimental data. Furthermore, unlike other existing methodologies that are limited to the use of hourly global horizontal irradiance, this model can be used with either instantaneous measurements or any averaged values. Nonetheless, it is limited to surfaces that are not affected by artificial horizon effects, which happen when the sun is at low elevations and obstructed by the surrounding structures.

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[17] This value is 0.35 for uncolored concrete, and 0.94 ± 0.02 for silver [17].

4.6 Miscellaneous models

4.6.1 CO_2 emissions from electricity generating systems

In this model, CO_2 emissions from several electricity generating systems are analyzed, based on a work published in [23]. In the original work, the process analysis method is used to analyze the CO_2 emission rates from manufacturing of PV modules and wind generators. In addition, the interindustry table is used to analyze the CO_2 emission rates from manufacturing of batteries and diesel generators. All of the CO_2 emission rates also include the emissions from manufacturing of other equipments used in each of the power systems. The results from these methods are shown in table 4.6.

electricity generating system type	*manufacturing CO_2 emission rate*
PV (based on a 100-kW model) with poly-Si PV array, stand and inverter	0.267 t-CO2/ kW·y
Wind generator (based on a 250-kW model) with rotor, generator, nacelle, speed accelerator, brake, and tower	0.069 t-CO2/ kW·y
Diesel generator	0.066 t-CO2/ kW·y
Battery	0.062 t-CO2/ kW·y

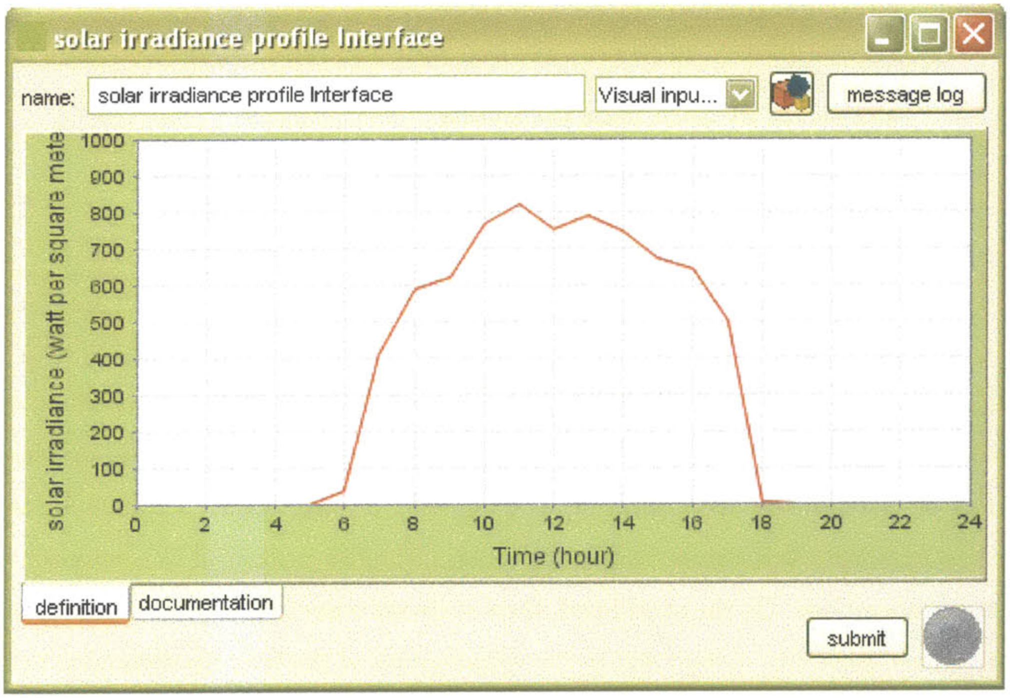
Table 4.6: Manufacturing CO2 emission rates of electricity generating systems.

Using these emission rates, the model can calculate the manufacturing CO_2 emission from any of the systems with a given output power and period of analysis. For the PV, battery, and wind generator systems, the manufacturing CO_2 emission of each system accounts for nearly all of the system's total emission, since there is no, or negligible, amount of CO_2 emission during the systems' operations. On the other hand, there is always some CO_2 emission during the operation of the diesel generator system due to the consumption of the fuel. To determine this emission, the model first calculates the diesel fuel consumption rate, using the same, statistically derived, formula that is also used in the diesel system's energy analysis model. With the calculated fuel consumption rate, together with the fuel's CO_2 emission rate, the model can then determine the diesel generator system' operating CO_2 emission. Finally, the total CO_2 emission of all systems combined can also be determined.

The accuracy of this model depends on the accuracy of the process analysis method and the interindustry table used to calculate the manufacturing CO_2 emission rates . In the derivations of the values used in this model, the lifetimes of a PV module, a wind generator, a diesel generator, and a battery are assumed to be 20, 15, 15, and 6 years, respectively [23]. In addition, it should be noted again that the formula for calculating the fuel consumption rate is statistically derived from data in literature review [32].

4.6.2 Solar irradiance profile

This model is custom-developed for the toolkit to provide an easy and convenient way for the users to form a profile of solar irradiance. Specifically, the model has a custom user interface containing an interactive chart, as shown in figures 4-11. The users can click on the chart and directly manipulate the plot of the profile. (See figure 4-12). Inside the model, the data of the profile is stored in two vectors: one for the time series and the other for the solar irradiance series. For the sample profile in figure 4-12, the data is shown in the table 4.7.



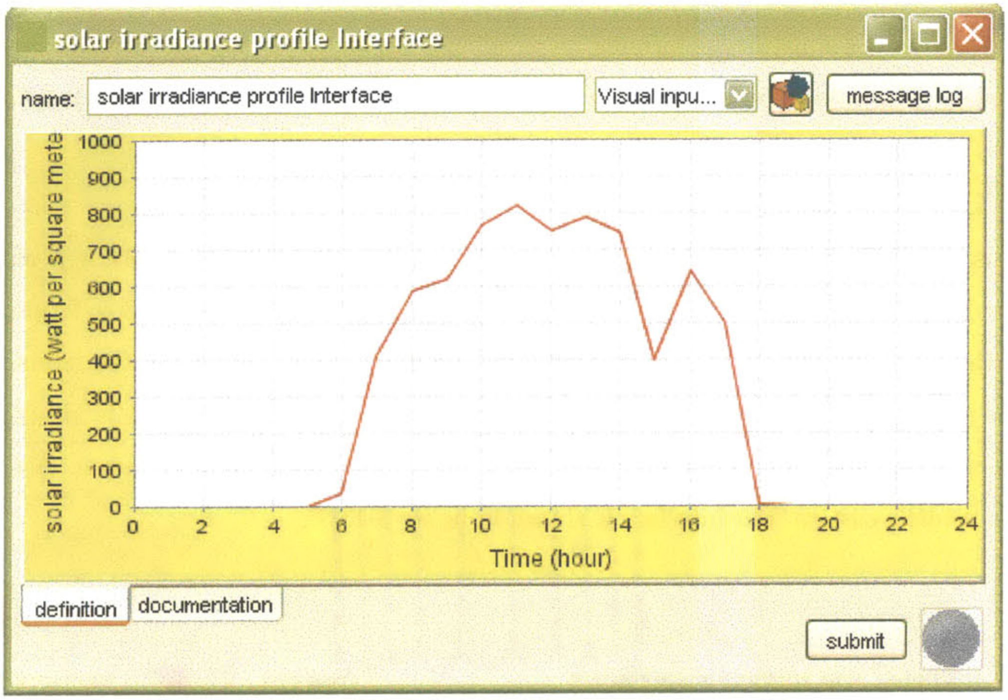
solar irradiance profile Interface

name: solar irradiance profile Interface

Visual inpu...

Figure 4-11: Custom interface with an interactive chart for forming a profile of solar irradiance.

Note that the data is specified at discrete time intervals, such as, in this case, at every hour. However, the users are free to specify the size of the time intervals. In addition, the irradiance



name: solar irradiance profile Interface

Figure 4-12: Updated profile after a user's click on the chart.

time (hr)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
irradiance (W/m^2)	0	0	0	0	0	0	36	407	586	618	765	821	749	786	746	401	642	500	4	0	0	0	0	0

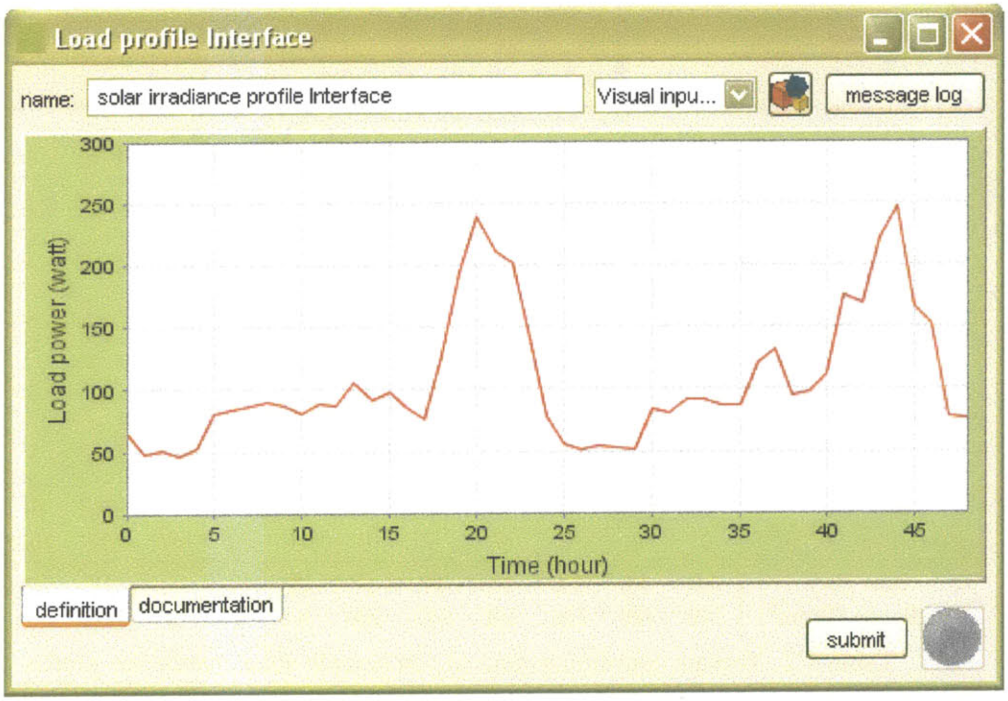
Table 4.7: Vectors containing data of the sample solar irradiance profile.

data can be retrieved at any time instant, even though the data is not explicitly specified for that instant. In that case, the model will interpolate the data from the vectors. For example, to retrieve the irradiance data at 13.5 hr, the model interpolates the data at 13 and 14 hrs, and obtains the irradiance of 766 W/m^2.

This model is useful for forming an irradiance profile to be used in integration with other models. The interactive chart allows the users to visualize the profile while it is being formed.

4.6.3 Load profile

This model functions in an exact same way as the previous model. Namely, it is also custom-developed for the toolkit to provide an easy and convenient way for the users to form a profile of, in this case, electricity load demand. Everything in the model, including the interactive chart and the method for interpolating data, is also the same. In addition, it is also particularly useful for forming a load profile for an integrated modeling of a power system. A snapshot of the model's custom user interface is shown in figure 4-13.



name: solar irradiance profile Interface

Visual inpu...

Figure 4-13: Custom interface with an interactive chart for forming a profile of electricity load demand.

Chapter 5

Sample design scenarios

To demonstrate the use of the Alternative Energy Design Toolkit, two sample design scenarios are created. The first scenario involves a design of a stand-alone PV system, and the second one involves a hybrid electricity generating system. Both of the scenarios show how the models from the toolkit can be easily integrated and how different analysis tools can be applied to the designs.

5.1 Scenario I: Design of a stand-alone PV system

In this scenario, a design of a stand-alone PV system is considered. The PV system consists of a PV array, a battery, an inverter, and a controller. The system receives energy from the incident solar irradiance, converts it into electricity, and delivers it to the load demand. Stand-alone PV systems are often used in areas that are disconnected from the grid. In this case, the design is for a typical remote island in the south of Thailand.

The models from the toolkit are used to create a representation of the PV system, to simulate its operation, and to predict its performance over a period of 48 hours. As indicators of performance, many of the system's characteristics, such as the voltage and current of the battery, are monitored.

5.1.1 Components models

To create a representation of the PV system, six models from the toolkit are utilized:

- Solar irradiance profile
- PV array operation
- PV system controller operation
- Lead-acid battery operation
- Inverter operation
- Load profile

In the solar irradiance profile model, the irradiance profile is formed for a period of 48 hours. (See figure 5-1). This profile represents the typical solar irradiance in Thailand's dry season[1], when the maximum solar irradiance is about 800 W/m^2. In addition, the second half of the profile is assumed to be cloudier than the first half. The data of the profile is entered in one-hour intervals.

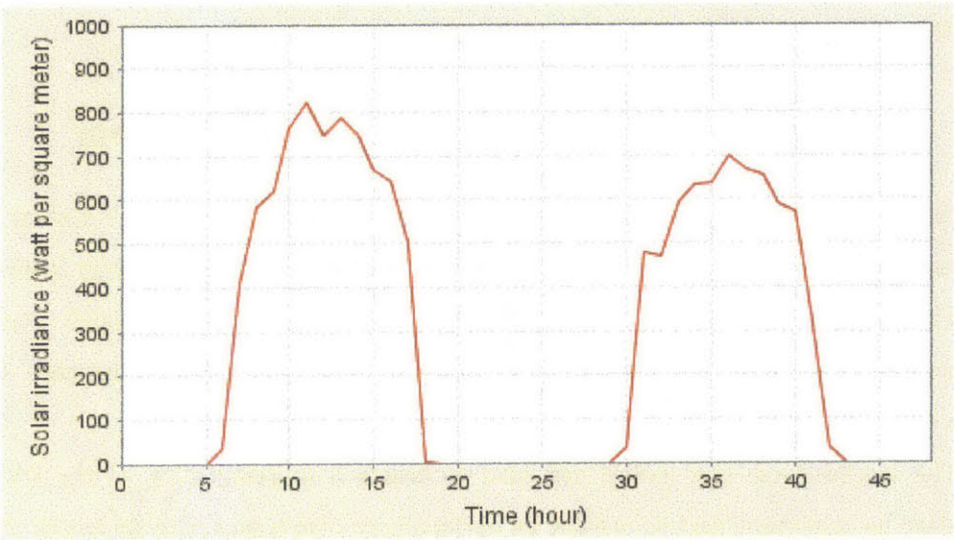


Figure 5-1: Solar irradiance profile used in design scenario *I*.

The PV array operation model is used to represent the PV array in the design. The PV array considered in this design is the same as the one considered in [45], with key specifications

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[1] The dry season takes place from November to May, with the following conditions: 2-3 m/s of averaged wind speed, 800 W/m^2 of maximum solar irradiance, and 25 – 31°C of temperature.

as follow. The array has 4 and 2 modules connected in parallel and series, respectively. The modules have a tilt angle of 15° and a terminal voltage of 12 V. The solar cells are made of crystalline silicon, whose band-gap energy is about 1.16 eV, and have a total area of 0.41 m^2 per module. In addition, each module has an absorption coefficient of 0.73 and the total area of 0.617 m^2. Other specifications of the modules, which are also used as inputs for the model, are listed in the appendix.

The controller considered in this design has a current loss of 0.01 A, and the voltage settings as shown earlier in table 4.1. As for the battery considered in this design, it has 12 2-V cells with a maximum state of charge of 1200 Wh. The charging and discharging efficiency is 0.8, while the self-discharging rate is 0.001 h^{-1}. The inverter considered in this design is also the same as the one in [45]. The variable and fixed loss coefficients of the inverter are available as 1.1885 and 10.045 W, respectively. Also, the inverter's terminal voltage is 24 V.

Lastly, the load profile model is used to form a profile for a period of 48 hours as well. (See figure 5-2).

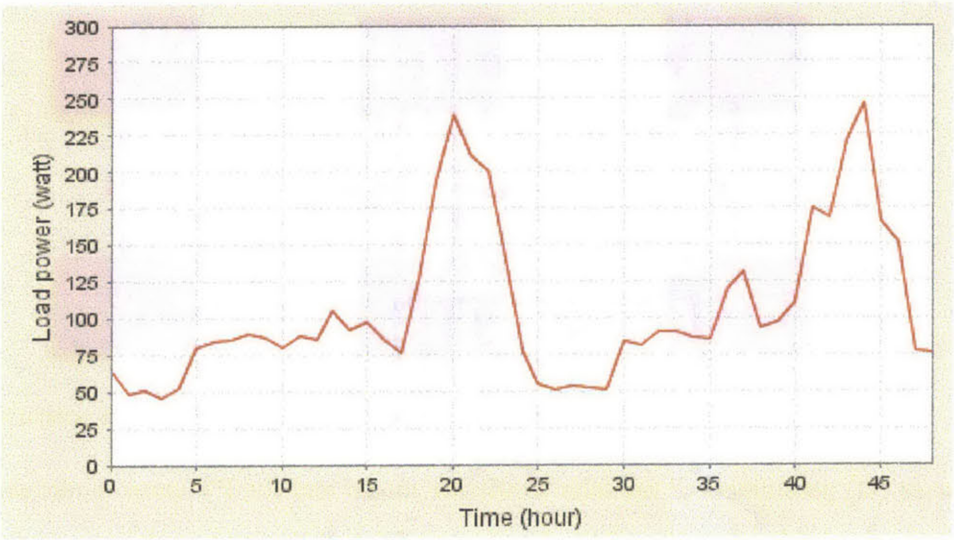


Figure 5-2: Load profile used in design scenario *I*.

Assuming that the remote island has 200 residents in 35 households, the daily averaged load is set at 60 kWh. The common components of the load are:

- 60 W incandescent lamps

- 20 W and 40 W fluorescent lamps
- 70 W and 75 W television sets
- 10 W radios
- 1 kW electric irons and fans

It is also assumed that the load is relatively higher during the evening, when the lamps and television sets are used. All of the input values of this load model, as well as the other components models used in this design scenario, are provided in the appendix.

5.1.2 Integration of models

After all the ingredient models are subscribed, as shown in figure 3-12, an integration model is added to the simulation in order to connect the models together. As discussed in the previous chapter, all connections are made declaratively. (See figure 5-3). First, the *instantaneous irradiance* (G) parameters of the solar irradiance model and the PV array model are connected. Next, the *load* (L) parameter of the inverter model and the load model are connected. Then, connections are made between the following parameters: the *PV-generated current* (I_{PV}) parameters of the PV array model and the controller model; the *load current* (I_l) parameters of the controller model and the inverter model; and the *battery current* (I_{bat}) and the *battery voltage* (V_{bat}) parameters of the battery model and the controller model.

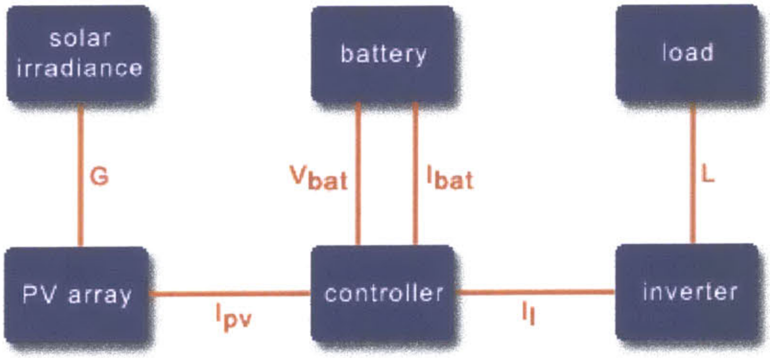


Figure 5-3: Declarative connections between the models in design scenario *I*.

Based on the internal causality of each model, DOME automatically figures out the directions of the information flows, as seen in figure 5-4. At this point, the integration can simulate the operation of the PV system and determine its characteristics *only* at one given time instant per execution. However, to truly understand and accurately assess the system's performance, the integration has to simulate the system over a sufficiently long sequence of time instants. In addition, the determined system's characteristics of one time instant have to be used as a basis for the simulation of the system at the next time instant.

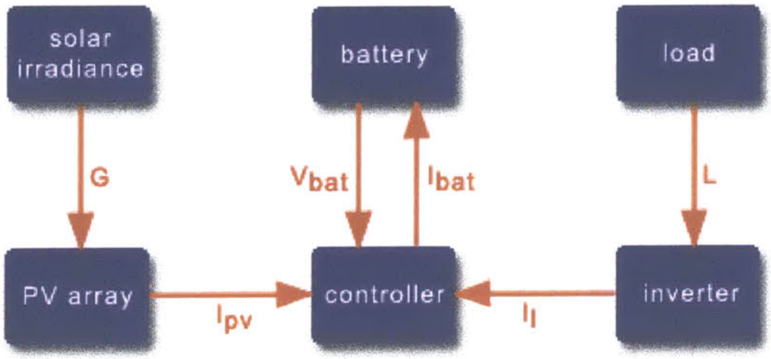


Figure 5-4: Information flows between the models in design scenario *I*.

To achieve the course of action mentioned above, the time iteration mechanism of DOME is utilized in the integration. A *time index* (t) parameter is added to the integration model and is used to drive the time index parameters in the solar irradiance and load models. (See figure 5-5). The time index starts at 0 hour and is increased by 0.5 hour every time the simulation is iterated until it reaches 48 hours, making the total of 97 iteration steps in the simulation. At the end of each iteration step, which is when all of the system's characteristics are already determined, the values of the characteristics are used to setup new starting values for the next step. For example, at the end of one iteration step, the PV array model has already determined the change in the solar cells' temperature. This change is used to calculate the new starting value of the solar cell's temperature (T_p) for the next iteration step. The same procedure is done for the system's status, denoted as "status" in figure 5-5, held by the controller. The system's status, whether BCM, FCM, or LVD, is determined by the controller model. At the end of the iteration step, the values of the status are set as the new starting values for the model in the

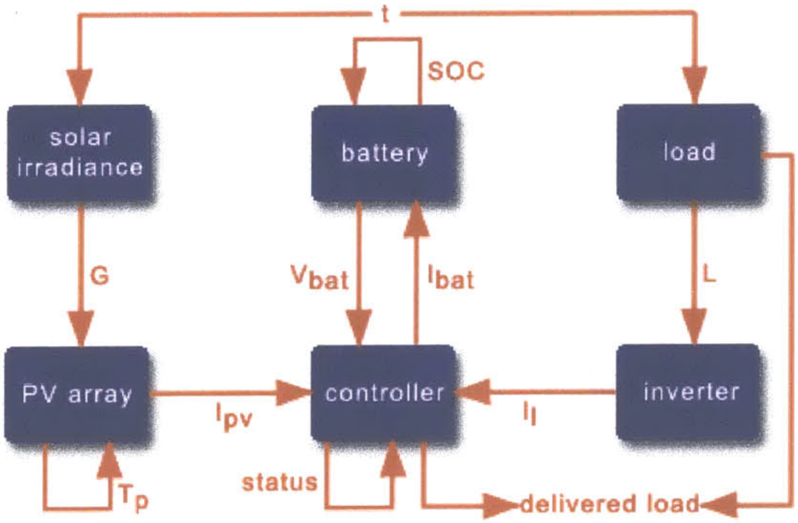


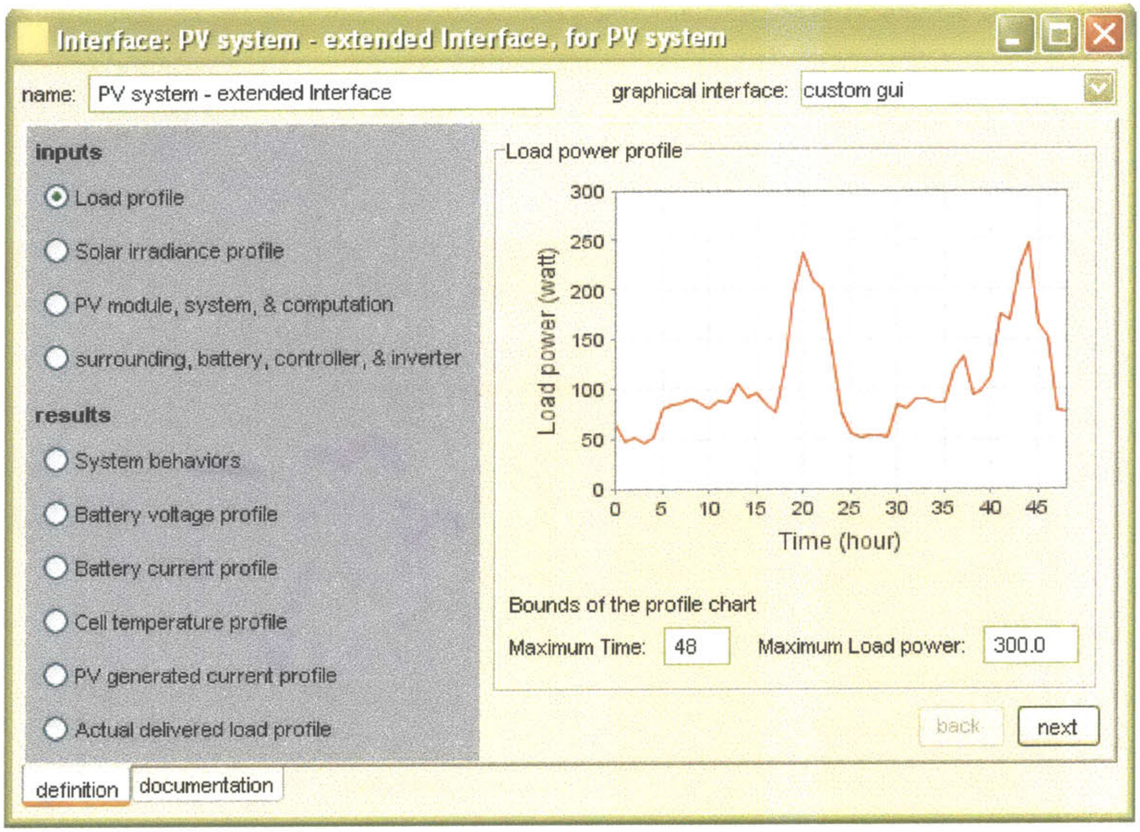
Figure 5-5: The integration after being added with a time iteration in design scenario *I*.

next step. Lastly, the same procedure is also applied to the battery's state-of-charge (SOC). After one iteration step, the battery model can determine the change in the state-of-charge as a result of some charged, or discharged, current. The change is also used to setup the new starting state-of-charge to be used in the next iteration step. As a result of the time iteration, the integration can realistically simulate the operation of the system.

Furthermore, the integration can also monitor the system's characteristics of interest throughout the simulation. The characteristics of interest include the battery's voltage and current, the solar cells' temperature, the PV-generated current, and the delivered load. These characteristics can be considered as measures of the system's performance. Particularly, the delivered load is the ultimate measure of performance, since it indicates whether or not the system supplies electricity to the load as demanded. The value of delivered load is calculated by the integration model, based on the system's low-voltage-disconnect (LVD) status, as indicated by the controller's model, and the instantaneous load demand from the load model. Unless the LVD is activated, the load is always delivered as demand; otherwise, the delivered load is zero.

5.1.3 Customized user interface

Making use of DOME's ability to support a customized graphical user interface (GUI), a GUI is created for the integration. The main purpose of this customized interface is to help organize the large number of parameters and to make the integration easier to understand. As shown


Interface: PV system - extended Interface, for PV system

name: PV system - extended Interface

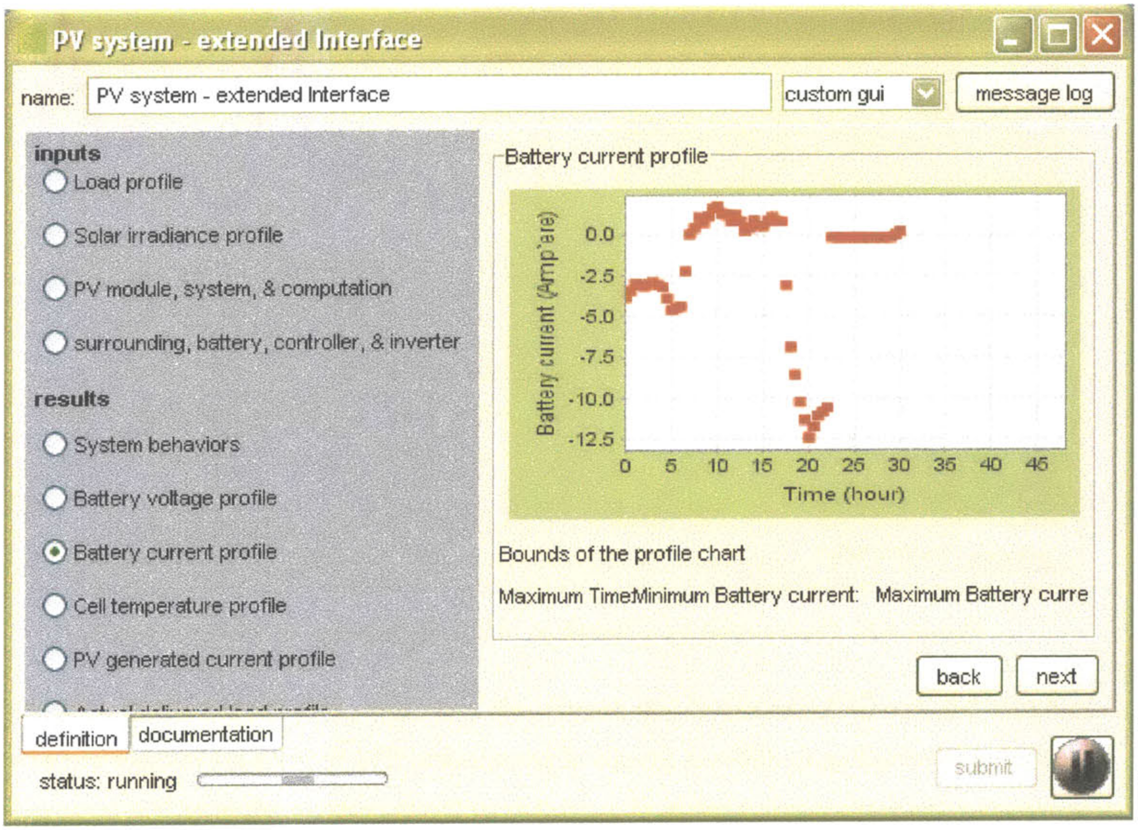
graphical interface: custom gui

Maximum Time: 48

Maximum Load power: 300.0

Figure 5-6: Customized user interface of the integration in design scenario *I*.

in figure 5-6, the GUI consists of two panels: left and right. The left panel has a list of radio buttons corresponding to different groups of parameters. The buttons are categorized as inputs or results. The right panel consists of a number of layers corresponding to the buttons in the left panels. When a button is selected, the corresponding layer in the right panel will come forward. For example, in figure 5-6, the layer containing load profile input parameters is shown, as the corresponding "Load profile" button is selected. In summary, there are four layers for the users to enter input values. The first two layers have an interactive chart to allow the users to conveniently form the profiles of load and solar irradiance. In addition, there are six layers presenting the results from the simulation. While the first result layer provides several important numerical results, the other five layers provide a plot of the system's important characteristics, as already mentioned above. During the simulation, the plots of the results are updated after every iteration step. (See figure 5-7). This way, the users can observe the system's characteristics in real-time. If the results already appear to be unsatisfactory for the users, they can immediately stop the simulation, try new values of the system's settings, and restart the simulation, instead of having to wait for the whole simulation to finish in order to find out the results.



name: PV system - extended Interface

Bounds of the profile chart

Maximum TimeMinimum Battery current: Maximum Battery curre

status: running

Figure 5-7: Plot of the battery current while being updated after every iteration step, in design scenario *I*.

5.1.4 Results and discussion

With the settings discussed in the "Components models" subsection, the simulation of the PV system obtains the results as shown in figures 5-8 to 5-12. Note that because of the limited space, only the plot areas of the results, in the right panel of the customized interface, are shown, instead of the whole interface.

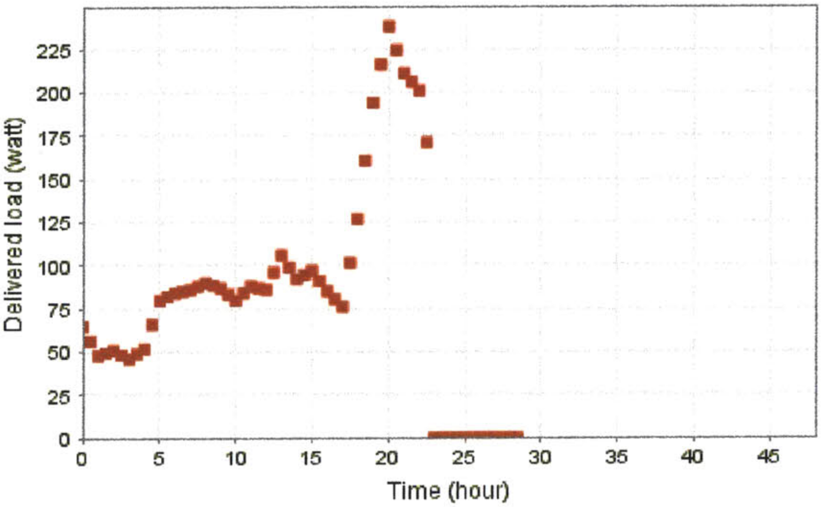


Figure 5-8: Prediction of delivered load demand in simulation #1 of design scenario *I*.

This simulation is terminated after the 29th hour , since the plot of the delivered load (figure 5-8) clearly indicates that the system cannot satisfy the load demand. In other words, the value of the delivered load is zero, starting at the 23rd hour. The zero delivered load also indicates that the system's low-voltage-disconnect (LVD) mode is activated by the controller. The activation of the system's LVD mode is due to the fact that, at the 23rd hour, the battery's voltage drops below the disconnect voltage value of 22.6 V, which is set to prevent a damage of the battery from being over-discharged. (See figure 5-9). It can also be seen that the battery's voltage starts dropping sharply around the 18th hour, or 6 PM. This is because the solar irradiance is no longer available for the PV array to generate electricity (see figure 5-10). Thus, there is no electric current flowing in to charge the battery, as can be seen in figure 5-11 that, after the 18th hour, the value of the battery's current becomes negative quickly. Once the load is disconnected from the system at the 23rd hour, the battery's current becomes zero, since there is no current

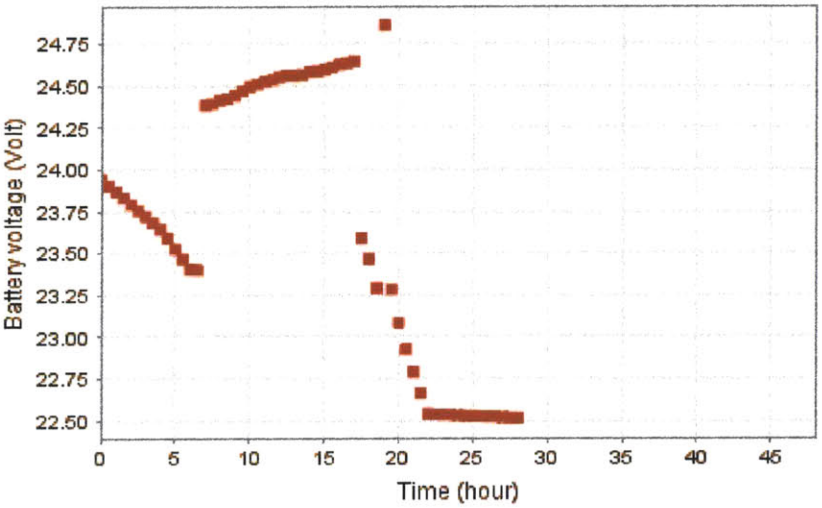


Figure 5-9: Prediction of battery's voltage in simulation #1 of design scenario *I*.

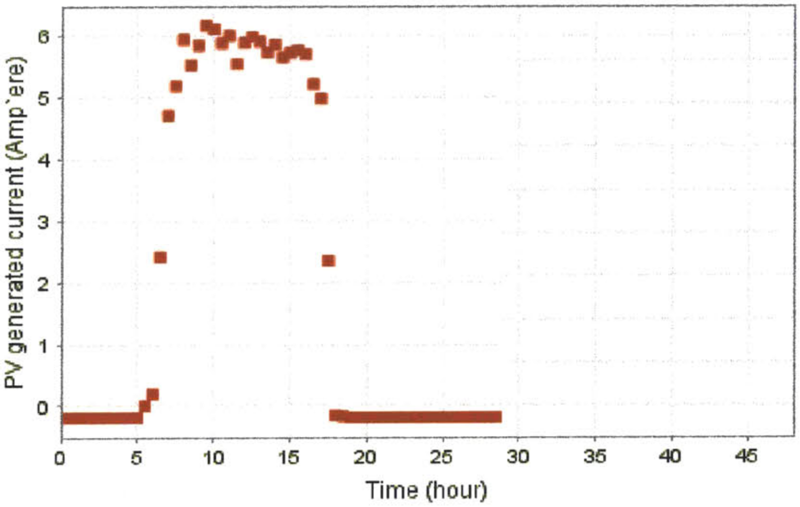


Figure 5-10: Prediction of PV-generated current in simulation #1 of design scenario *I*.

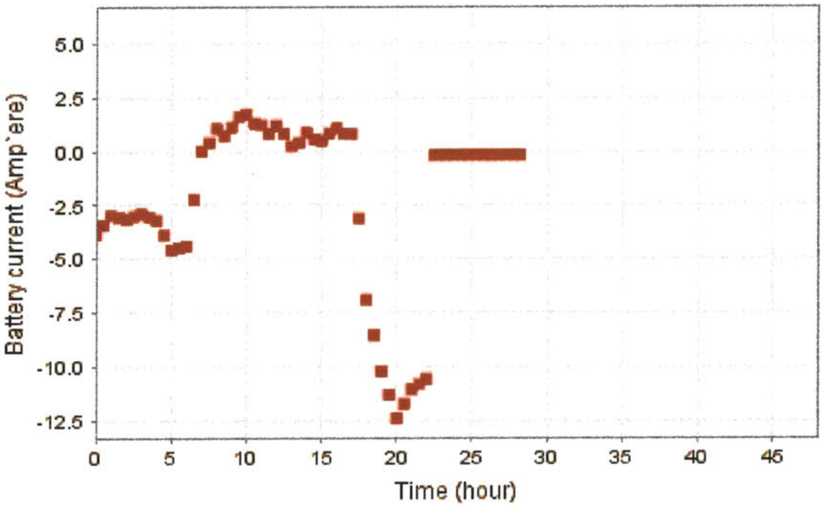


Figure 5-11: Prediction of battery's current in simulation #1 of design scenario I.

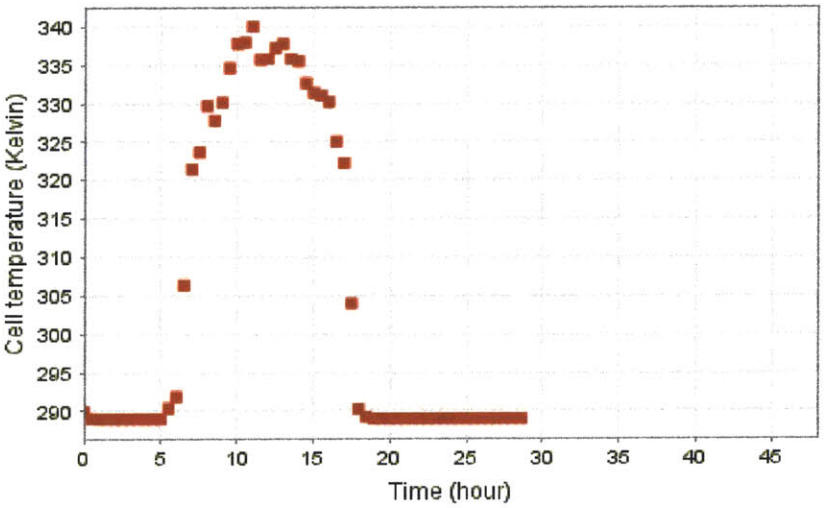


Figure 5-12: Prediction of solar cells' temperature in simulation #1 of design scenario I.

going in or out of the battery. Lastly, figure 5-12 simply illustrates that the temperature of the solar cells is relatively low at night and high during the day. Also, the shape of the solar cells' temperature profile closely resembles that of the solar irradiance profile, shown in figure 5-1.

It can be concluded from the simulation's results that there is not enough energy stored in the battery to deliver to the load at night. The problem is not because the battery's capacity is too low. Figure 5-9 shows that the battery's voltage is far from being overcharged, since the battery's maximum floating voltage is 27.8 V. Therefore, the problem must be because, during the day, the PV array does not generate enough electricity to charge the battery to a sufficiently high voltage. This problem can be solved by increasing the number of solar modules in the array.

In the next simulation, the number of PV modules connected in parallel is increased to 12, making the total of 24 modules in the array, from previously 8. All of the other settings of the system are kept the same. The plots from the results of this simulation are shown in figures 5-13 to 5-17.

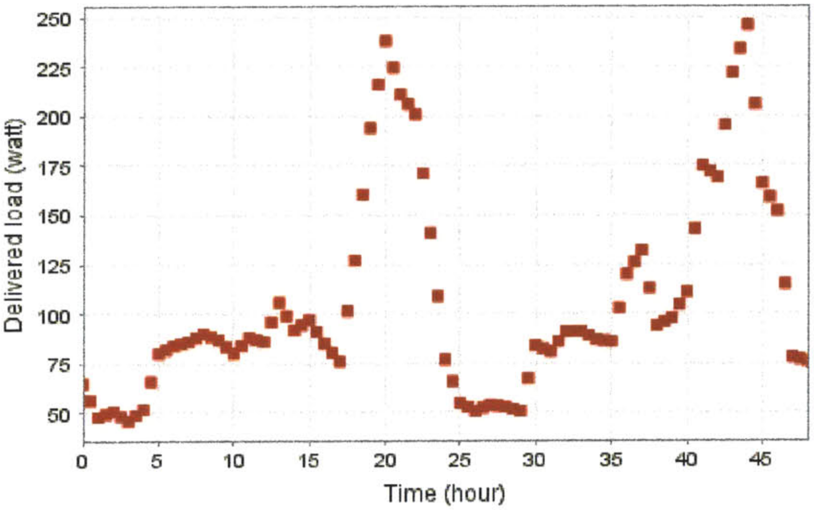


Figure 5-13: Prediction of delivered load demand in simulation #2 of design scenario *I*.

With the new settings, the PV system can successfully fulfill the electricity load demand, as seen in figure 5-13, where the shape of the delivered load profile matches exactly with that of the load demand, shown in figure 5-2. As figure 5-14 shows, the battery's voltage also stays in a good range throughout the analysis. In fact, so much electricity is generated and charged to

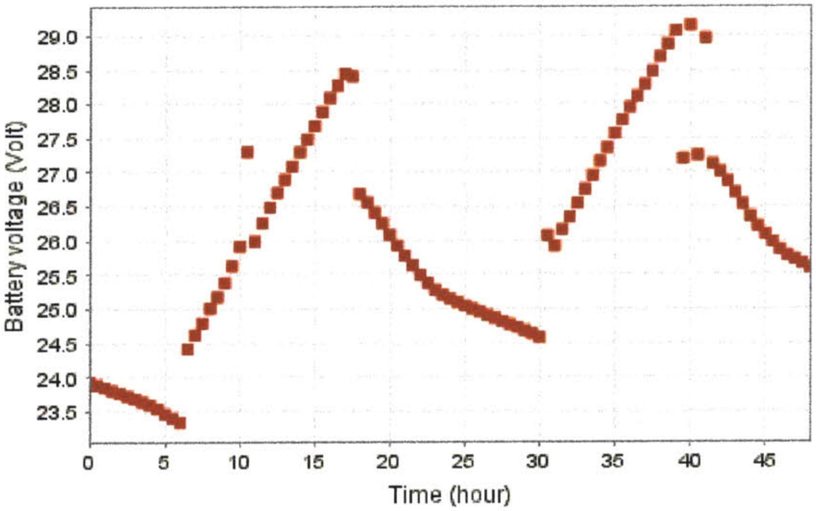


Figure 5-14: Prediction of battery's voltage in simulation #2 of design scenario *I*.

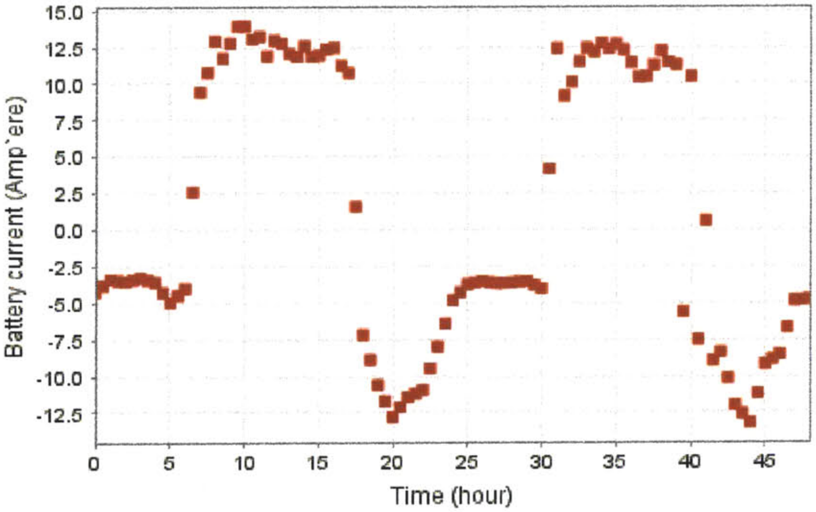


Figure 5-15: Prediction of battery's current in simulation #2 of design scenario *I*.

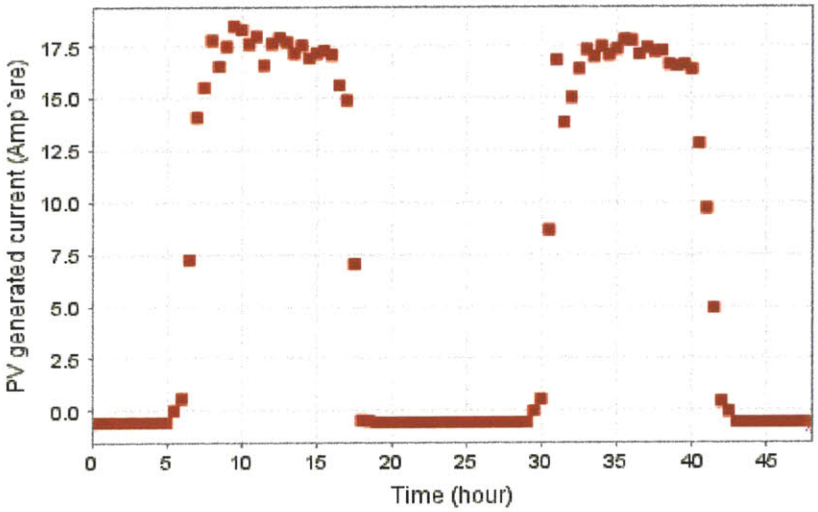


Figure 5-16: Prediction of PV-generated current in simulation #2 of design scenario I.

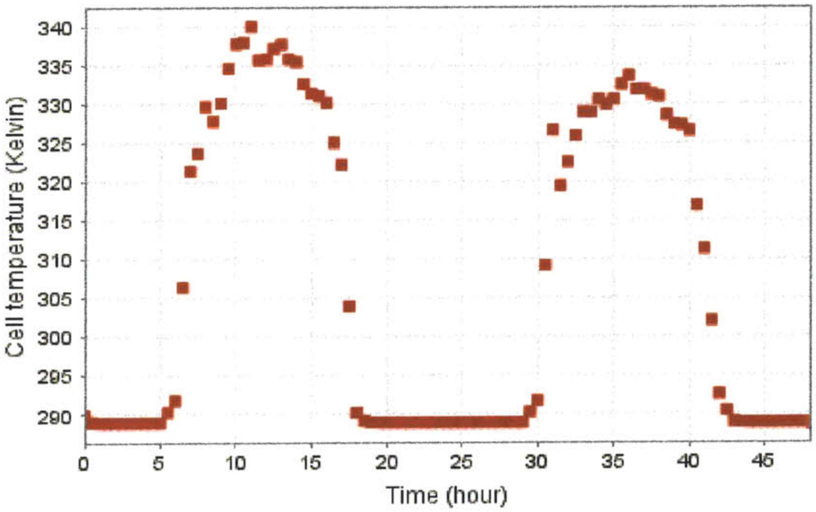


Figure 5-17: Prediction of solar cells' temperature in simulation #2 of design scenario I.

the battery that its voltage rises beyond the boost voltage around the 40th hour. At that point, the controller switches the battery into the float-charge mode (FCM) and disallows further charging to prevent it from being overcharged. Similarly, figure 5-15 also confirms that the battery operates normally throughout the analysis period, since electric current is charged to and discharged from the battery regularly. Lastly, figures 5-16 and 5-17 show the profiles of the PV-generated current and the solar cells' temperature. The shapes of both profiles closely resemble that of the solar irradiance profile in figure 5-1.

5.1.5 Summary

The models in the toolkit are proven to be useful and convenient resources for creating a representation of a stand-alone PV system. With DOME as the toolkit's enabler, the integration of the models is done straightforwardly. In addition, the time iteration mechanism helps the integration accurately simulate the operation of the PV system. Furthermore, taking advantage of the ability to support a customized GUI, a customized interface is created for the integration. The interface helps organize the parameters in the integration and make it easy to use. Also, with the real-time plots of the results, the interface allows the users to closely monitor the simulation. Moreover, the quick and easy setup of the simulation makes it easy for the users to try out different settings for the system. Ultimately, this integration allows the users to interactively design the PV system.

5.2 Design scenario II: Trade-off analysis of a hybrid PV-diesel system

In a hybrid PV-diesel system, a diesel generator is used in addition to a PV array to generate electricity. In most applications, the PV array is used as a main component, while the diesel generator is used as a backup. To most system designers, PV arrays are often considered as environmental-friendly, but costly. In contrast, diesel generators are often considered as non-environmental-friendly, but economical. In this design scenario, a representation of a hybrid PV-diesel system is created, and the system's performance is analyzed in terms of costs, CO_2 emission, and energy consumption.

This design scenario is also assumed to take place in an island in southern Thailand, and the analysis is for a period of 20 years of the system's operation. In the scenario, the PV array and the diesel generator co-generate the electricity for the load. The amount of electricity generated by each component corresponds to a specified PV load fraction. Ranging from 0 to 1, the fraction is a design parameter that specifies how much of the total load is to be delivered by the PV. The PV array operates during the daytime, while the diesel generator operates for a certain number of hours as specified. Both of the PV load fraction and the number of diesel operating hours are considered as design parameters. The design objectives are the system's capital cost, life-cycle cost, net electricity cost, CO_2 emission, and electricity production efficiency.. By varying the design variables, different values of the objectives can be obtained, and certain values of the design variables that lead to desirable values of the objective can be chosen.

5.2.1 Components models

Six models from the toolkit are used:

- PV system load breakdown
- PV system life-cycle costing
- Engine-generator system life-cycle costing
- Simplified PV module and battery energy analysis
- Simplified diesel generator energy analysis
- CO_2 emissions from electricity generating systems

The net daily load of the island is assumed to be 4,071 Wh, with the daytime load of 37% of the net load. In addition, about an average of 13.5 hours per day is assumed to have sufficient solar irradiance for the PV array. These values are necessary inputs for the PV system load breakdown model. The other inputs needed for this model are the battery's charging efficiency, discharging efficiency, and minimally allowed normalized state-of-charge. These values are set as 0.8, 0.95, and 0.7, respectively, for this design scenario.

For the costing models, the discount rate and excess inflation are set at typical values of 0.1 and 0, respectively [29]. The individual costs of the components in the system, as well as the components' maintenance costs, are based on statistical values from the literature reviews [36]. All of the values are listed in the appendix.

While the lifetimes of the PV array and the battery are set as 20 and 5 years, respectively, the diesel generator's lifetime, which depends on the type of the engine, is implicitly set by the simulation. Specifically, a 3000-rpm diesel engine has a lifetime of 6000 operating hours, while the 1500-rpm one lasts for 10000 hours. The values of the other components' lifetime are also listed in the appendix.

Similarly, the energies required for material processing, manufacturing, distribution, installation, O&M, and end-of-life management for the PV array, battery, and diesel generator are also listed in the appendix. Nevertheless, it is worth noting that, for the diesel generator, a significant portion of the system's energy input is from the fuel, whose heating value is 10.08 kWh/l.

For the CO_2 emission model, important inputs are the rates of emissions associated with the fuel consumption and the manufacturing of the PV array, battery, and diesel generator. The values are 2.45 kg/l and 0.267, 0.062, and 0.069 t/kW-yr.

5.2.2 Integration of models

The integration of the models in this design scenario requires a number of calculations in order to make connections between the models. The calculations are required mostly because the inputs to different models may be related but not exactly the same. For example, while the diesel generator cost model requires the amount of the annually diesel-generated electricity as an input, the CO_2 emission model needs the value of the total diesel-generated electricity over the entire analysis period. In this case, the known value of the annually generated electricity can be inputted directly to the cost model; however, the value needs to be multiplied by the number of the analysis's years, to obtain the total value, which can then be inputted to the CO_2 emission model.

The integration model handles these calculations, as shown in figure 5-18. It starts by calculating the amounts of loads need to be delivered by the PV array and the diesel generator,

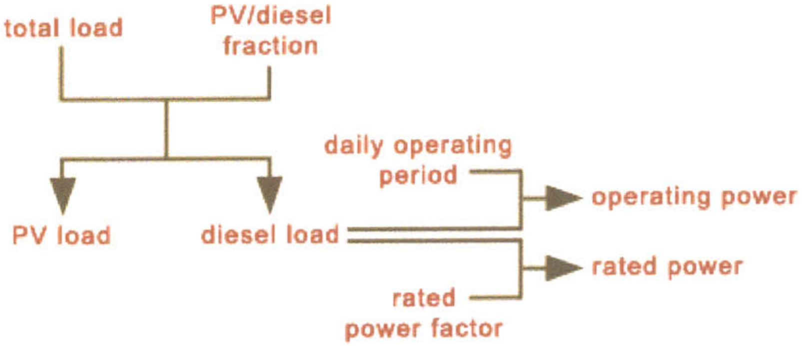


Figure 5-18: Calculations in the integration model of design scenario II.

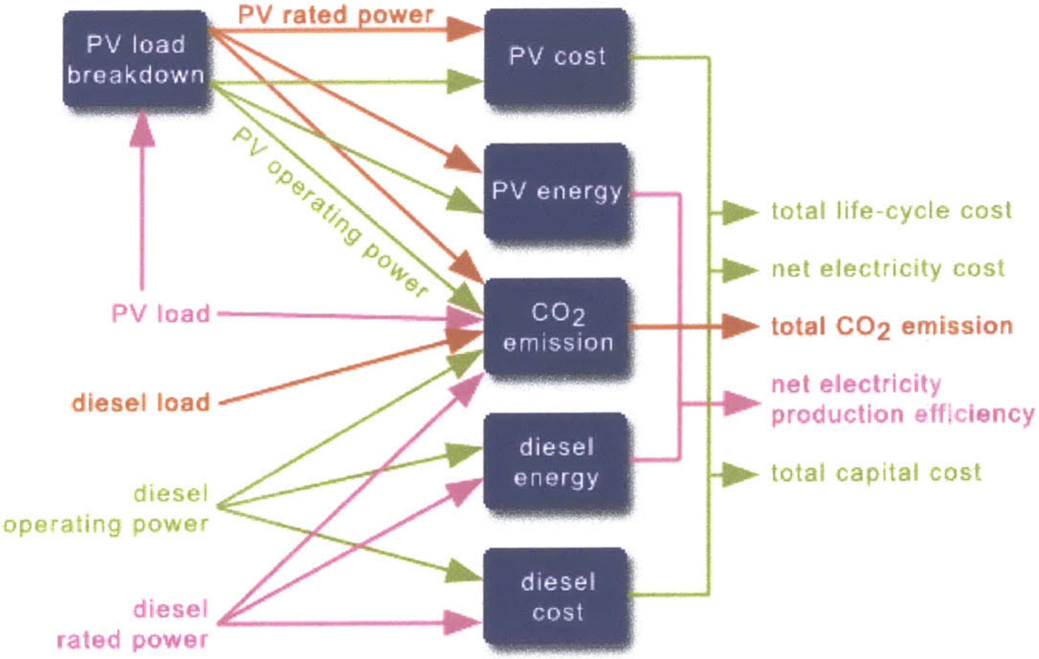


Figure 5-19: Connections between the models in the integration of design scenario II.

based on the total load and the specified PV load fraction. With the calculated diesel load, the integration model can then determine the necessary operating and rated powers of the diesel generator, based on the specified daily operating period and the rated power factor of the generator. As mentioned earlier, the daily operating period indicates the number of hours of the generator's operation in a day. The rated power factor is a safety factor for determining the generator's nominal power for a given operating power. For example, if a load power of 100 W is needed, and the rated power factor is 1.3, then a generator with a manufacturer's rated power of 130 W should be used.

The determined values of the PV array's and diesel generator's loads, and the generator's operating and rated powers are used as inputs for the models in the integration. The outputs from the models are combined to obtain the values of the five design objectives: total life-cycle cost, net electricity cost, total CO_2 emission, net electricity production efficiency, and total capital cost. All of the connections between the models in the integration are shown in figure 5-19. As always, the connections are made declaratively, and DOME automatically determines the directions of the information flows.

5.2.3 Customized user interface

This integration also makes use of DOME's ability to support a customized graphical user interface. The customized interface created for this integration is intended to help organize the large number of parameters and also to make the integration easier to understand. Like the customized interface of the previous scenario, this one also consists two panels, with the left one containing a lists of buttons and the right one containing layers corresponding to the buttons. There are six layers totally:

- design parameters , and inputs for the properties of energy and CO_2 emission
- inputs for the properties of load, diesel generator, and PV array
- inputs for the costs and economics
- design objectives , and results for the properties of energy and CO_2 emission
- results for the properties of load, diesel generator, and PV array

- results for the costs and economics

Snapshots of the customized interface with each these layers visible are shown in the appendix.

5.2.4 Design-scan analysis

The design objectives indicate the performance of the hybrid system, and the design parameters represent the settings. With the current integration, the performance of the system can be evaluated for only one setting at a time. In this way, the users have to use a trial-and-error approach to obtain desired values of the design objectives, or even just to understand the trend of how the design variables affect the objectives.

To understand how each of the design variables affects the design objectives, a design-scan analysis is applied to the integration. The design-scan analysis simulates the integration for all combinations of values from the whole ranges of the design variables. In this case, the value of the PV load fraction ranges from 0 to 0.95, with an increment of 0.05. The value of the diesel operating period ranges from 1 to 24 hours, with an increment of 1 hour. Consequently, the design-scan analysis simulates the integration for a total of 480 combinations of values of the design variable or, in other words, 480 different settings of the system. The values of each design objectives, obtained from all simulations, are saved in a file and can be presented in a three-dimensional plot.

5.2.5 Results and discussion

Figures 5-20 to 5-24 show three-dimensional plots of the each design objective versus the two design variables. Figure 5-20 shows that for a given diesel operating, the capital cost increases when more load is assigned to be delivered by the PV array. Also, for a given PV load fraction, the capital cost rises sharply when diesel generator is set to operate for only a few hours in a day. In addition, the lowest capital cost can be achieved by assigning the entire load to the diesel generator and allow it to operate for 24 hours a day. However, figure 5-21 shows that such setting would result in the highest life-cycle cost. Therefore, the setting with the lowest cost to build will, in fact, costs the most after a long period. Furthermore, the setting that is initially expensive to build will actually cost the least in a long run.

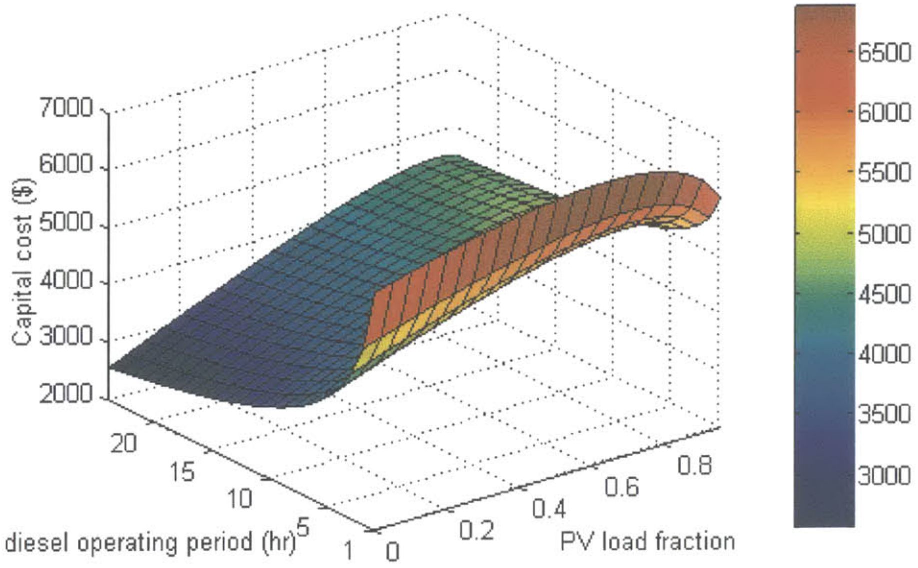


Figure 5-20: Capital cost of the hybrid system in design scenario *II*.

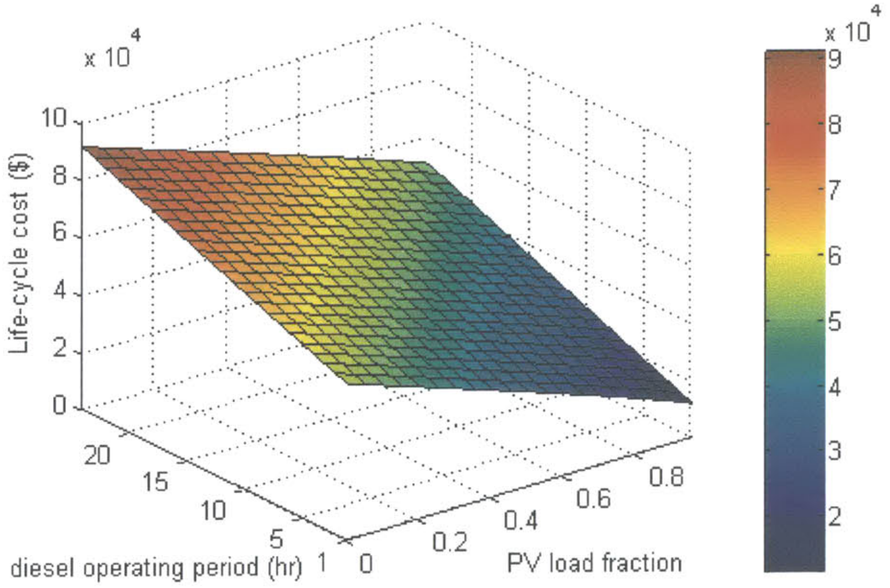


Figure 5-21: Life-cycle cost of the hybrid system in design scenario *II*.

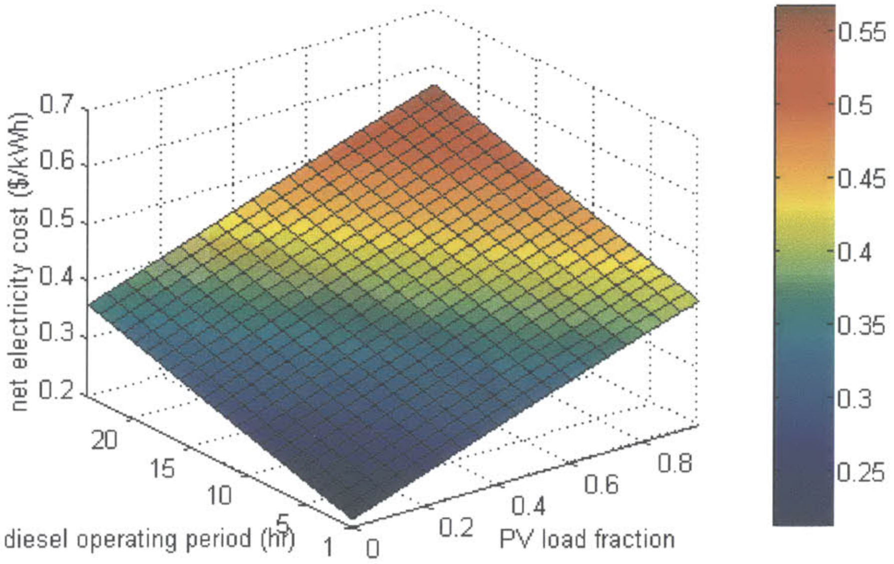


Figure 5-22: Net electricity cost of the hybrid system in design scenario *II*.

Nevertheless, as shown in figure 5-22, the settings that lead to the lowest capital and life-cycle costs both result in a moderate net electricity cost, about 0.4 $/kWh. The setting the results in the lowest net electricity cost is to assign the entire load to the diesel generator and to make it produce electricity for all the load in only one hour. However, that setting emits the highest amount of CO_2, as shown in figure 5-23. The setting with the lowest CO_2 emission is the one that assigns 95% of the load to PV and let the diesel generator run for 24 hours a day to produce its part of the load.

Lastly, figure 5-24 illustrates the electricity production efficiency of the hybrid system. As mentioned earlier, the electricity production efficiency is a ratio of the total energy output and the total energy input of the system. It is an indicator of how efficient the system converts the input energy into electricity. The figure shows that the hybrid system is highly efficient when most of the load is assigned to the PV array. Also, for a given PV load fraction, the efficiency is almost independent of the daily operating period of the diesel generator.

The results from the design-scan analysis become particularly useful when used collectively. Each of the objectives may be more important than the others, depending on the design applications. For example, if the hybrid system is to be used in a private resort on the island, the

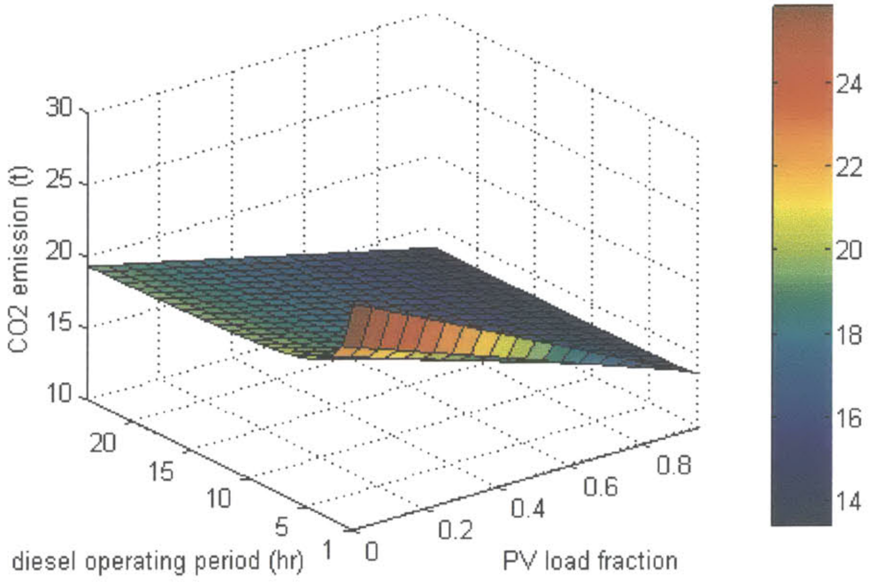


Figure 5-23: CO_2 emission of the hybrid system in design scenario II.

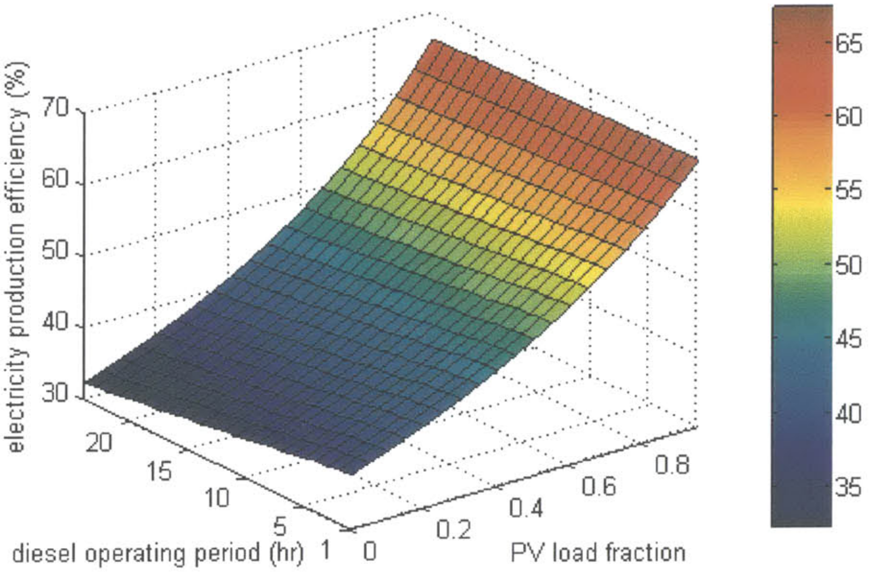


Figure 5-24: Electricity production efficiency of the hybrid system in design scenario II.

most important objective for the owner may be to build a system with the lowest total life-cycle cost. As discovered earlier, the system with the lowest total life-cycle cost assigns 95% of the load to the PV array and let the diesel generator produce the other 5% of the load within an hour a day. With this system, however, the owner needs to make an expensive initial investment on the system. Nonetheless, the system is highly efficient and emits the lowest amount of CO_2. The electricity cost is not relevant, since the electricity is not to be sold to anyone.

Another example of a design application is a governmental subsidization of a hybrid system to provide electricity to the islanders at an affordable cost. In this case, the most important objective is the net electricity cost. The setting that results in the lowest electricity cost is the one that assigns the entire load to the diesel generator and has it all produced within an hour a day. However, this setting is impractical for many reasons. First of all, the capital cost of the system is very high and might be over the government's budget. In fact, to keep the capital cost low, the diesel generator should operate longer than about 10 hours a day. In addition, the setting with the lowest electricity cost is not very efficient and, most importantly, leads to an extremely high amount of CO_2 emission. On the other hand, the government may be more likely to afford a system that is set up such that about 40% of the load is delivered by the PV array and the diesel generator's load is produce within about 10 hours a day. With this system, the capital, life-cycle, and net electricity costs are relatively low. Although the system has a moderate efficiency, its CO_2 emission is relatively low. Thus, this system's setting more applicable for this design application.

5.2.6 Summary

The models in the toolkit are proven to be useful and convenient resources for analyzing the performance of the hybrid PV-diesel system. The model integration is straightforward, even with the additional calculations required to connect the models. A customized user interface is also created for the integration to make it easier to use and understand. With the utilization of the design-scan analysis, the trends of how the design variables affect the design objectives can be discovered. The results from the design-scan analysis are also proven to be useful for selecting and assessing different system configurations for different design applications.

Chapter 6

Conclusions

6.1 Summary

In chapter 2, the alternative energy design tools are categorized by the ranges of renewable energy technologies that the tools can consider. The first category includes the tools that handle virtually all renewable energy technologies. Only two prominent examples, HOMER and RETScreen, are found in this category. The second category includes the tools that consider a small set of renewable energy technologies. For most tools in this category, the technology that is always present is photovoltaic panels. With a small number of technologies in consideration, this group of tools can afford more detailed modeling of designs. The tools in the third category support only one specific renewable energy technology. Most of the tools in this category are related to solar energy technologies, especially photovoltaic and solar heating collector. Furthermore, there is a special category that includes the tools developed especially for building applications. The most common building applications considered in these tools are lighting, heating, cooling, ventilation, and hot water supply.

After all of the tools in the survey are discussed, observations are made from the tools' common characteristics, advantages, and disadvantages. From the observations, a number of characteristics that an effective renewable energy design tool should possess are summarized. The key characteristics include easy and broad accessibility, flexibility and easy expansion of modeling, optimization of designs, multiple user interfaces, simple incorporation of third-party models, and support for collaborative designs.

In Chapter 3, the details of the Alternative Energy Design Toolkit are provided. First, the model collection is discussed. The collection provides models of fundamental components commonly used in renewable energy design processes. Each model in the collection is a modular entity and can function independently. The models can be flexibly combined to create different representations of energy systems. Many of the models have multiple forms of user interfaces tailored for different usages. Most of the models were found in scientific journals or technical books and are proven to be reliable. The other models are custom-developed for the toolkit based on simple logic. The implementation of mathematical relations in the models are done in DOME as much as possible, in order to eliminate the need for third-party programming software. Beside the models that are already included, more models, after being certified, can be contributed to the toolkit by the users. The model contributions can expedite the expansion of the collection and promote knowledge sharing among the users.

In the following section, DOME, as an enabler of the toolkit, is discussed. DOME is an implementation of the WWSW concept. In DOME, the users' ideas, in forms of models, are shared and made assessable through the internet. DOME supports a customized user interface and provides several visualizations to make the models easier to use and understand. In addition, color-coded computation-status feedback is also provided to make the computations in DOME more transparent and comprehendible. Implementations of new models, as well as wrapping of third-party models in DOME can be done straight-forwardly. Furthermore, live models can be integrated to represent a system. Connections between parameters in the integration are made in a declarative fashion, and the models used as the integration' s resources can be distributed over different servers. To simulate the integration, DOME relies on the individual models in the integration as autonomous, local servers that share their own causality information with each other and solve themselves. With these characteristics of DOME, a representation of a system can be built in an ad-hoc way. In addition, the users of DOME can collaborate in a playspace, where they can input their opinion on a design, discuss problems, and try out different options together on a live design simulation. Lastly, the users can use the built-in optimization tool to help make an informed and effective design decision.

The last section of chapter 3 presents the details of the toolkit's supporting Web site. The Web site serves as a bridge that makes the models in the WWSW accessible from the WWW.

The site is a host of a DOME Web applet that lets the users from anywhere with an internet access make use of DOME and the WWSW. Moreover, the Web site is a center for models and ideas transactions. The users of the toolkit are highly encouraged to exchange ideas and models through requests and contributions of models. In addition, the Web site also serves as a knowledge base, where documentations of models and information about the toolkit and subjects related to renewable energies are provided.

In chapter 4, solar energy models in the toolkit are presented. These models are the initial set of models that are implemented for the toolkit. The models are categorized by their functions. The first category consists of the models of PV operation and components in PV systems, including PV arrays, batteries, controllers, and inverters. The next category contains the models related to flat-panel solar collectors. The third category includes the models for analyzing the economic aspect of PV and diesel generator systems. The following category contains the energy analysis models. The next category includes the models for calculating solar irradiance. Lastly, miscellaneous models, including the CO_2-emission model, are included in the last category. For all of the models, detailed explanations of the subject matters and the mathematical relations are also discussed.

Chapter 5 provides two design scenarios as examples of the toolkit's applications. The design scenario *I* concerns design of a stand-alone PV system. Six models from the toolkit are integrated to create a representation of the system. After the time-iteration mechanism is applied to the integration, the system's operation is simulated and the characteristics are monitored. The monitored characteristics are the battery's voltage and current, the PV-generated current, the solar cells' temperature, and the load satisfied by the system. In the first simulation, the system is found to be undersized, as the battery's voltage lowers to a dangerous level and the load is then cut off from the system. The number of PV modules is increased in the second simulation, this time the system successfully generates enough electricity for the load.

In the design scenario *II*, the performance of a hybrid PV-diesel electricity generating system is investigated. Particularly, the system's capital cost, life-cycle cost, net electricity cost, electricity production efficiency, and CO_2 emission are the design objectives, which are considered as the measures of the system's performance. The design-scan analysis is applied to the integration. The analysis simulates the integration for all combinations of values from the whole ranges of the design variables, which are the PV load fraction and the diesel generator's operating period. Three-dimensional plots of the design objectives are obtained and used to configure the system for different design applications. For the private-resort application, the system performs most effectively when configured to have 95% of the load delivered by the PV array, while the other 5% is generated by the diesel generator within only an hour a day. However, for the governmental subsidization case, the system is more effective when 40% of the load is delivered by the PV array and the diesel generator produce the other 60% within about 10 hours a day.

The models in the toolkit are proven to be useful and convenient resources for both design scenarios. The processes of making the representations of the systems are straight-forward, and the analysis mechanisms that the toolkit provides make the design process simple yet effective.

6.2 Future work

Besides completing the development of the supporting Web site, there are a few other missions to undertake. The first mission to study the related tools and their models in more details, in order to determine if there will be any benefits from wrapping those models for the toolkit. The tools that will be focused on initially are those that are meant to be used by the public, such as RETScreen. Incorporating the models from these tools will help broaden and diversify the subject matters covered by toolkit.

In addition, in order to explore energy systems specific to the needs of a particular country or region, a few outreach initiatives are planned. One of the initiatives to be undertaken in the near future is with the city of Cambridge, where the city planners are eager to promote the use of renewable energy to the community. Specifically, there will be collaboration with the Environmental Policy Group of the MIT Department of Urban Studies and Planning, starting in the upcoming semester, to advocate the Alternative Energy Design Toolkit as an online resource for the community. The initial target group of this initiative is the home owners, who effectively are in control of making decisions regarding energy use in their houses, e.g. whether they should energy-saver light bulbs, or whether they should install photovoltaic modules on their roof, etc. The toolkit will assist the home owners in many aspects, ranging from making simple modeling of their energy use scenarios, to predicting the benefits and tradeoffs of renewable energy designs. In addition to the home owners in the city of Cambridge, the use of the toolkit will be expanded to the business and industrial sectors, both in the city of Cambridge and nearby cities such as Newton and Boston.

Additionally, collaboration is planned with Thailand's Metal and Material Technology Center (MTEC). MTEC is a state-agency research institute that works closely with the industrial sector in Thailand. Some of MTEC's main projects involve ecological & economic design and renewable energy technologies. The technologies and knowledge gained by MTEC are frequently transferred to industry and, hence, have important influence on development within the country. From the collaboration with MTEC, the real problems currently being faced, especially those involving development of renewable energy systems, can be identified. In addition, the promotion of the Alternative Energy Design Toolkit is anticipated for practical use by industries in Thailand.

Ultimately, it is hoped that the toolkit will help expedite the progression of renewable energy systems.

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Appendix A. Summary of related work survey

properties	HOMER	RETScreen
commercial software		
spreadsheet-based format		✓
modular structure / toolkit style		
integration of multiple programs or softwares		
easy accessibility for public	✓	✓
features		
online forums or marketplace		✓
descriptions of models and algorithms / help		✓
optimization		
minimum costs (in some forms)	✓	
minimum power purchased from grid		
minimum loss of load probability		
optimal energy management /control		
result presented as a range of options	✓	
sensibility analysis	✓	✓
environmental impact assessment		✓
economic or financial analysis	✓	✓
database (weather, product specifications)		✓
dedicated simulation of physical properties		

Table 6.1: Tools that support all types of renewable energy technologies

properties	VT's	AUTH's	CMRESSS	AUA & NTUA's	IPSEpro & REYSYSpro	TREES
commercial software					✓	
spreadsheet-based format						✓
modular structure / toolkit style						
integration of multiple programs or softwares						
easy accessibility for public						✓
features						
online forums or marketplace						
descriptions of models and algorithms / help						
optimization						
minimum costs (in some forms)	✓					✓
minimum power purchased from grid	✓	✓				
minimum loss of load probability	✓					
optimal energy management /control				✓		
result presented as a range of options		✓				
sensibility analysis						
environmental impact assessment						
economic or financial analysis	✓	✓			✓	✓
database (weather, product specifications)						✓
dedicated simulation of physical properties	✓	✓	✓	✓	✓	

Table 6.2: Tools that support a few types of renewable energy technologies

properties	SimPhoSys	PV*SOL	NUS's	MUERI's	T*SOL	COSSOR	GSHP
commercial software		✓			✓		
spreadsheet-based format							✓
modular structure / toolkit style	✓			✓		✓	
integration of multiple programs or softwares						✓	✓
easy accessibility for public							
features							
online forums or marketplace							
descriptions of models and algorithms / help							
optimization							
minimum costs (in some forms)					✓		
minimum power purchased from grid							
minimum loss of load probability							
optimal energy management /control				✓			
result presented as a range of options							
sensibility analysis							
environmental impact assessment							
economic or financial analysis		✓			✓		
database (weather, product specifications)		✓					
dedicated simulation of physical properties	✓		✓	✓	✓	✓	✓

Table 6.3: Tools that support one particuclar type of renewable energy technology

properties	NTUA's	Wind Diesel Energy Design Toolkit	Biomass Toolkit
commercial software			
spreadsheet-based format			✓
modular structure / toolkit style		✓	✓
integration of multiple programs or softwares		✓	✓
easy accessibility for public			
features			
online forums or marketplace			
descriptions of models and algorithms / help			
optimization			
minimum costs (in some forms)	✓		✓
minimum power purchased from grid			
minimum loss of load probability			
optimal energy management /control	✓	✓	
result presented as a range of options			
sensibility analysis			
environmental impact assessment			
economic or financial analysis	✓	✓	✓
database (weather, product specifications)			
dedicated simulation of physical properties	✓	✓	✓

Table 6.4: Tools that support one particuclar type of renewable energy technology (cont.)

properties	ENERGY-10	Renew	FEDIC's	ISE's	Yemen's	Lightscape	IBDS
commercial software	✓					✓	
spreadsheet-based format							
modular structure / toolkit style							✓
integration of multiple programs or softwares							✓
easy accessibility for public		✓					
features							
online forums or marketplace							
descriptions of models and algorithms / help	✓						
optimization							
minimum costs (in some forms)	✓						
minimum power purchased from grid							
minimum loss of load probability							
optimal energy management /control	✓		✓				
result presented as a range of options	✓						
sensibility analysis							
environmental impact assessment	✓						
economic or financial analysis	✓	✓					✓
database (weather, product specifications)		✓					✓
dedicated simulation of physical properties	✓		✓	✓	✓	✓	✓

Table 6.5: Tools that support designs with renewable energy technologies for buildings

Appendix B. Data used in the sample scenarios

Design of a stand-alone PV system

Solar irradiance profile

time position	set by the integration model
time vector	0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 ... 17 18 19 20 21 22 23 24 25 26 27 28 29 30 ... 31 32 33 34 35 36 37 38 39 40 41 42 43 44 ... 45 46 47 48 hr
irradiance vector	0 0 0 0 0 0 36 407 586 618 765 821 749 786 ... 746 669 642 500 4 0 0 0 0 0 0 0 0 0 0 0 ... 35 480 471 591 632 639 697 670 654 589 569 ... 316 33 0 0 0 0 0 0 W/m^2

PV array operation

solar irradiance	set by the solar irradiance profile model	
ambient temperature	300	K
cell area	0.41	m^2
module area	0.617	m^2
module terminal voltage	12	V
number of module in parallel	4	
number of module in series	2	
time interval	1800	s
cell band gap energy	1.16000268	eV
ground emissivity	0.2	
ground temperature	300	K
material constant	7100	A/K^3
module absorption coefficient	0.73	
module diode series resistance	2.28	Ω
module diode shunt resistance	250	Ω
module diode ideality factor	38.59	
module temperature efficiency	0.0045	K^{-1}
module thermal capacity	9259	J/K
panel emissivity	0.88	
sky emissivity	1	
panel-ground view factor	0	
panel-sky view factor	1	
reference module efficiency	12	%
short-circuit constant coefficients 1	0.0041	m^2/V
short-circuit constant coefficients 2	-3.73 E-4	m^2/W
short-circuit constant coefficients 3	-0.00244	K^{-1}
tilt angle	15	°
wind speed	0.4	m/s
cell temperature	set by the output of this model after every time-iteration step	

PV system controller operation

boost voltage	28.8	V
battery voltage	set by the Lead-acid battery operation model	
maximum float voltage	27.8	V
minimum float voltage	25.2	V
reconnect voltage	26.8	V
disconnect voltage	22.6	V
controller loss current	0.01	A
PV array current	set by the PV operation model	
load current	set by the inverter operation model	
previous BCM status	set by the output of this model after every time-iteration step	
previous FCM status	set by the output of this model after every time-iteration step	
previous LVD status	set by the output of this model after every time-iteration step	

Lead-acid battery operation

charge/discharge efficiency	0.8	
self-discharge rate	0.001	h^{-1}
number of 2-V cells	12	
time interval	1800	s
integration time step	1	s
maximum SOC	1200	Wh
previous state's voltage	set by the output of this model after every time-iteration step	
previous state's normalized SOC	set by the output of this model after every time-iteration step	
battery current	set by the PV system controller operation model	

Inverter operation

variable loss coefficient	1.1885	
fixed loss coefficient	10.045	W
input voltage	12	V
output power	set by the load profile model	

Load profile

time position	set by the integration model
time vector	0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 ... 17 18 19 20 21 22 23 24 25 26 27 28 29 30 ... 31 32 33 34 35 36 37 38 39 40 41 42 43 44 ... 45 46 47 48 hr
load vector	65 48 51 46 52 80 84 86 90 87 80 88 86 106 ... 92 97 85 76 127 194 238 211 201 141 77 55 51 ... 54 53 51 84 81 91 91 87 86 120 132 94 98 111 ... 175 169 222 246 166 152 78 78 W

Trade-off analysis of a hybrid PV-diesel system

PV system load breakdown

daily generated electricity	4071	Wh
day hours	13.5	h
day load fraction	37	%
battery charging efficiency	80	%
battery discharging efficiency	95	%
battery minimum SOC	0.7	

PV system life-cycle costing

period of analysis	20	yr
discount rate	0.1	
excess inflation	0	
PV array lifetime	21	yr
array support lifetime	20	yr
battery lifetime	5	yr
PV module cost	3.74	\$/W
PV support cost	1.17	\$/W
battery cost	100	\$/kWh
power conditioner cost	0.64	\$/W
installation cost factor	20	%
annual O&M cost factor	2	%
battery size	set by the integration model	
PV array size	set by the integration model	
annual generated electricity	set by the integration model	

Engine-generator system life-cycle costing

period of analysis	20	yr
discount rate	0.1	
excess inflation	0	
engine type	1500-rpm diesel	
fuel storage cost	1.7	$/l
fuel storage size	50	l
engine oil price	3.9	$/l
oil change and air-filter cleaning cost	14.8	$
oil-filter replacement cost	52.8	$
air-filter replacement cost	54.6	$
fuel-filter replacement cost	54.6	$
spark plugs replacement cost	48.3	$
air-filter cleaning period	1	times per oil change
oil-filter replacement period	2	times per oil change
air-filter replacement period	4	times per oil change
fuel-filter replacement period	4	times per oil change
spark plugs replacement period	4	times per oil change
fuel cost	0.7	$/l
installation cost factor	15	%
annual operation time	set by the integration model	
engine-generator nominal power	set by the integration model	
engine-generator power	set by the integration model	
annual generated electricity	set by the integration model	

Simpified PV module and battery energy analysis

annual operation and maintenance energy	3	Wh/yr
period of analysis	20	yr
module installation energy	2.2	kWh
module end-of-life management energy	0.22	Wh
module distribution energy	10	kWh
PV module lifetime	21	yr
battery nominal capacity	set by the integration model	
PV nominal power	set by the integration model	
total output energy	set by the integration model	

Simpified diesel generator energy analysis

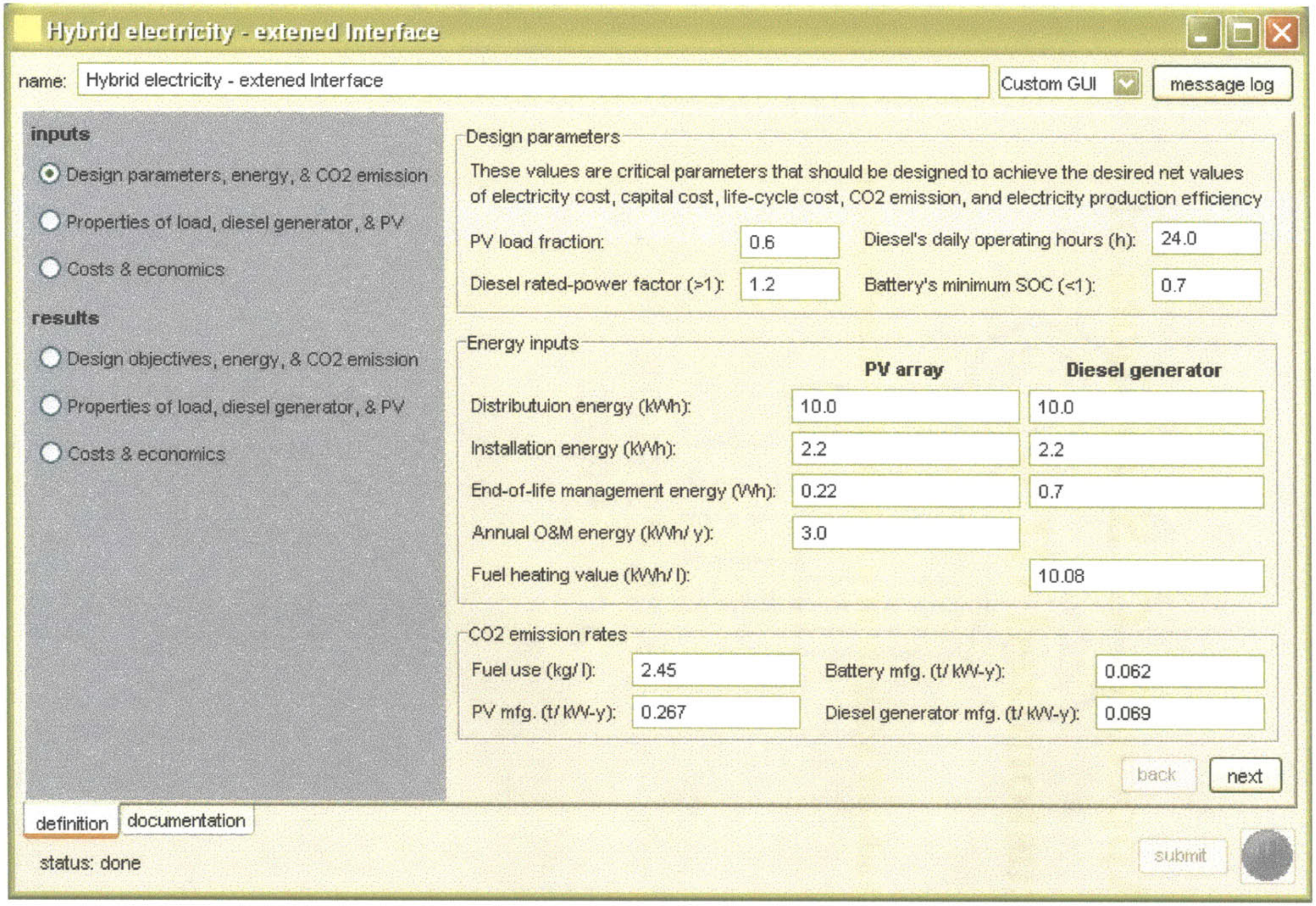
diesel heating value	10.08	kWh/yr
period of analysis	20	yr
installation energy	2.2	kWh
end-of-life management energy	0.7	Wh
distribution energy	10	kWh
PV module lifetime	21	yr
generator nominal power	set by the integration model	
generator power	set by the integration model	
total output energy	set by the integration model	

CO_2 emissions from electricity generating systems

period of analysis	20	yr
PV manufacturing CO_2 emission rate	0.267	t/kW−yr
diesel generator manufacturing CO_2 emission rate	0.062	t/kW−yr
battery manufacturing CO_2 emission rate	0.069	t/kW−yr
diesel generated electricity	set by the integration model	
fuel CO_2 emission rate	2.25	kg/l
generator power	set by the integration model	
PV nominal power	set by the integration model	
generator nominal power	set by the integration model	
battery nominal capacity	set by the integration model	

Appendix C. Snapshots of customized GUIs

Trade-off analysis of a hybrid PV-diesel system



Hybrid electricity - extened Interface

name: Hybrid electricity - extened Interface

inputs

● Design parameters, energy, & CO2 emission
○ Properties of load, diesel generator, & PV
○ Costs & economics

results

○ Design objectives, energy, & CO2 emission
○ Properties of load, diesel generator, & PV
○ Costs & economics

Design parameters

These values are critical parameters that should be designed to achieve the desired net values of electricity cost, capital cost, life-cycle cost, CO2 emission, and electricity production efficiency

PV load fraction: 0.6
Diesel's daily operating hours (h): 24.0
Diesel rated-power factor (>1): 1.2
Battery's minimum SOC (<1): 0.7

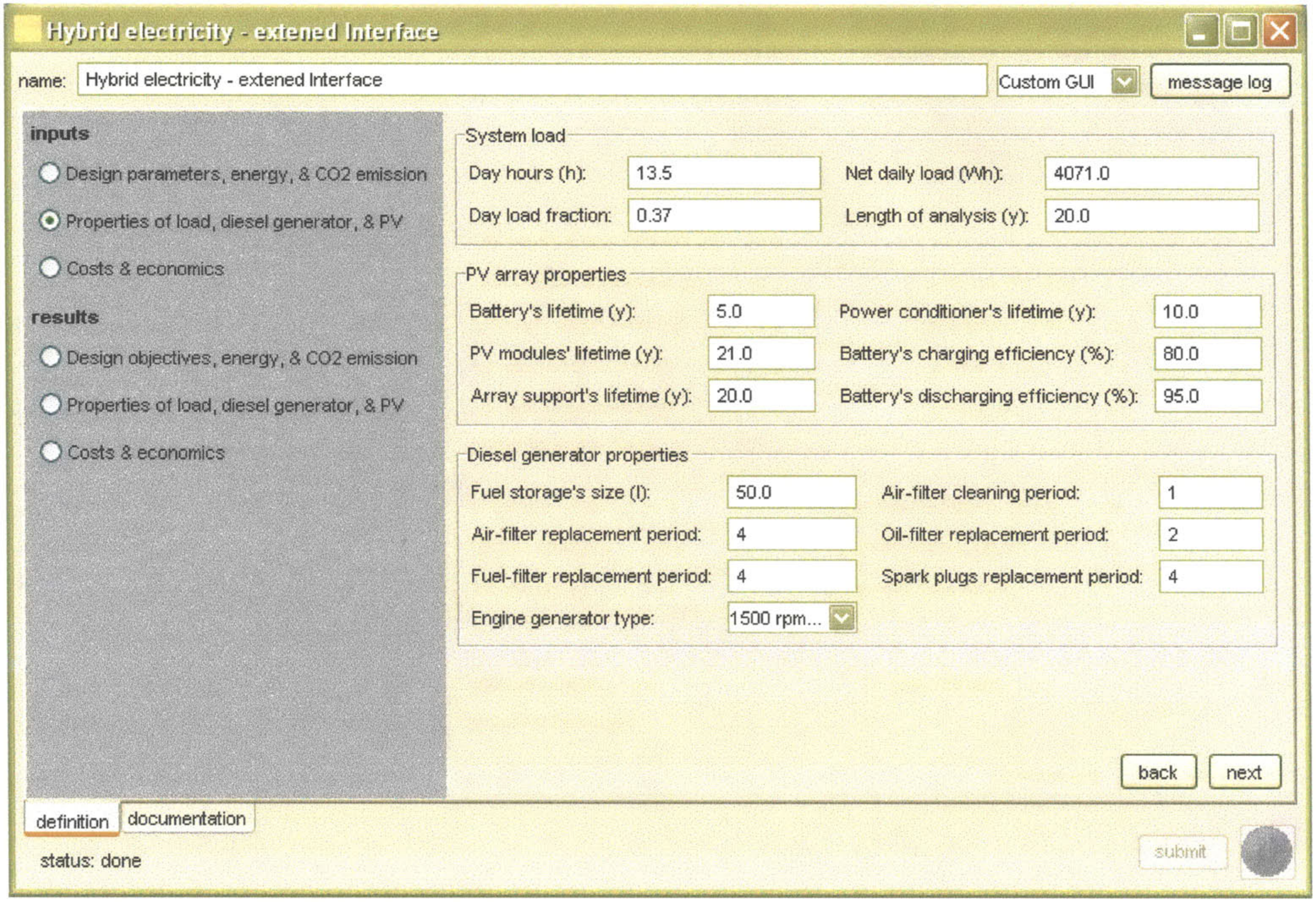
Energy inputs

	PV array	**Diesel generator**
Distributuion energy (kWh):	10.0	10.0
Installation energy (kWh):	2.2	2.2
End-of-life management energy (Wh):	0.22	0.7
Annual O&M energy (kWh/ y):	3.0	
Fuel heating value (kWh/ l):		10.08

CO2 emission rates

Fuel use (kg/ l): 2.45
Battery mfg. (t/ kW-y): 0.062
PV mfg. (t/ kW-y): 0.267
Diesel generator mfg. (t/ kW-y): 0.069

status: done



name: Hybrid electricity - extened Interface

System load

Day hours (h):	13.5	Net daily load (Wh):	4071.0
Day load fraction:	0.37	Length of analysis (y):	20.0

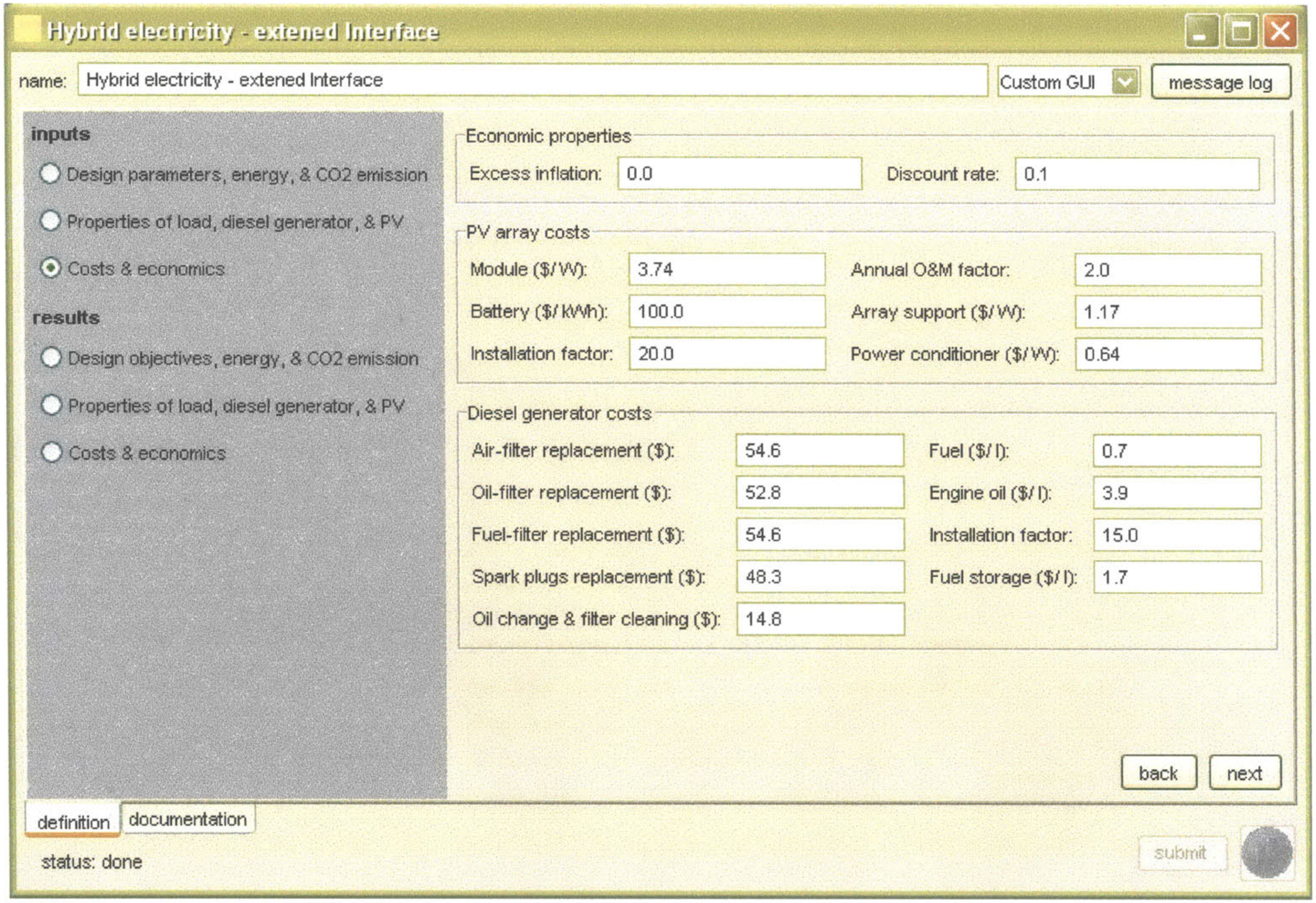
PV array properties

Battery's lifetime (y):	5.0	Power conditioner's lifetime (y):	10.0
PV modules' lifetime (y):	21.0	Battery's charging efficiency (%):	80.0
Array support's lifetime (y):	20.0	Battery's discharging efficiency (%):	95.0

Diesel generator properties

Fuel storage's size (l):	50.0	Air-filter cleaning period:	1
Air-filter replacement period:	4	Oil-filter replacement period:	2
Fuel-filter replacement period:	4	Spark plugs replacement period:	4
Engine generator type:	1500 rpm...		

status: done



Hybrid electricity - extened Interface

name: Hybrid electricity - extened Interface

Custom GUI

inputs

○ Design parameters, energy, & CO2 emission

○ Properties of load, diesel generator, & PV

● Costs & economics

results

○ Design objectives, energy, & CO2 emission

○ Properties of load, diesel generator, & PV

○ Costs & economics

Economic properties

Excess inflation: 0.0

Discount rate: 0.1

PV array costs

Module ($/W): 3.74

Annual O&M factor: 2.0

Battery ($/kWh): 100.0

Array support ($/W): 1.17

Installation factor: 20.0

Power conditioner ($/W): 0.64

Diesel generator costs

Air-filter replacement ($): 54.6

Fuel ($/l): 0.7

Oil-filter replacement ($): 52.8

Engine oil ($/l): 3.9

Fuel-filter replacement ($): 54.6

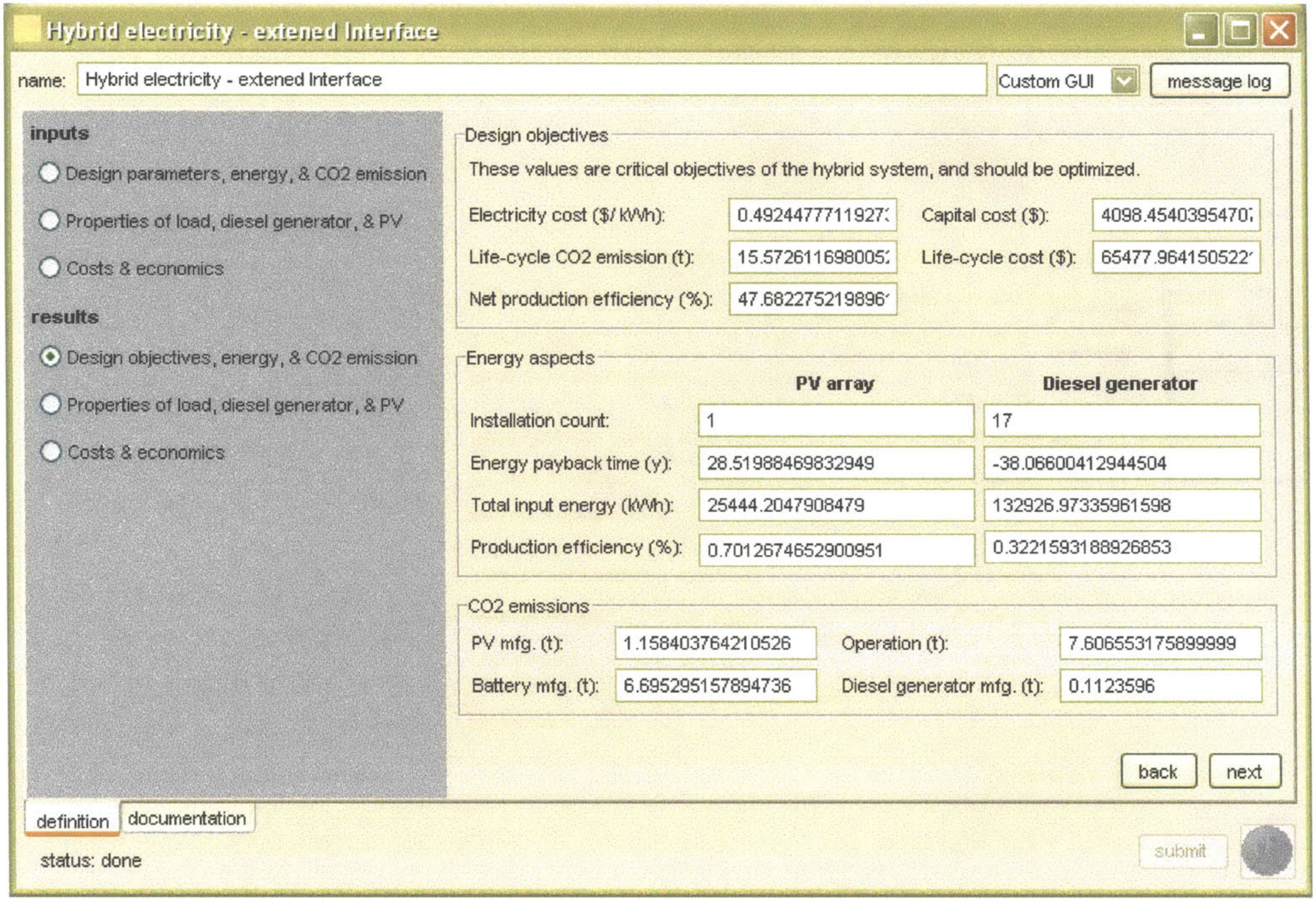
Installation factor: 15.0

Spark plugs replacement ($): 48.3

Fuel storage ($/l): 1.7

Oil change & filter cleaning ($): 14.8

status: done



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Design objectives

These values are critical objectives of the hybrid system, and should be optimized.

Electricity cost ($/ kWh):	0.4924477711927	Capital cost ($):	4098.4540395470
Life-cycle CO2 emission (t):	15.572611698005	Life-cycle cost ($):	65477.964150522
Net production efficiency (%):	47.682275219896		

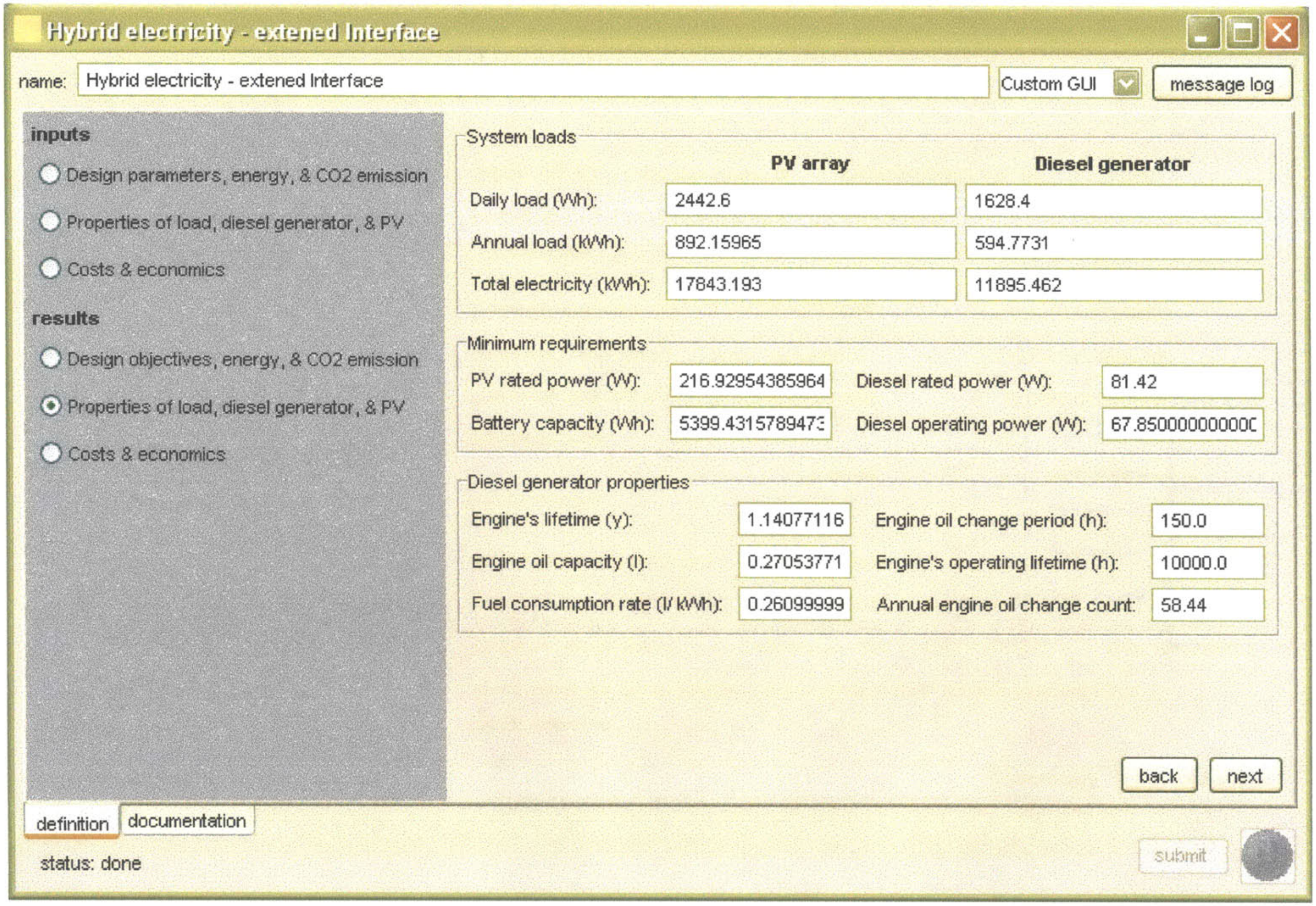
Energy aspects

	PV array	Diesel generator
Installation count:	1	17
Energy payback time (y):	28.51988469832949	-38.06600412944504
Total input energy (kWh):	25444.2047908479	132926.97335961598
Production efficiency (%):	0.7012674652900951	0.3221593188926853

CO2 emissions

PV mfg. (t):	1.158403764210526	Operation (t):	7.606553175899999
Battery mfg. (t):	6.695295157894736	Diesel generator mfg. (t):	0.1123596

status: done



name: Hybrid electricity - extened Interface

System loads

	PV array	Diesel generator
Daily load (Wh):	2442.6	1628.4
Annual load (kWh):	892.15965	594.7731
Total electricity (kWh):	17843.193	11895.462

Minimum requirements

PV rated power (W): 216.92954385964

Battery capacity (Wh): 5399.431578947

Diesel rated power (W): 81.42

Diesel operating power (W): 67.85000000000

Diesel generator properties

Engine's lifetime (y): 1.14077116

Engine oil capacity (l): 0.27053771

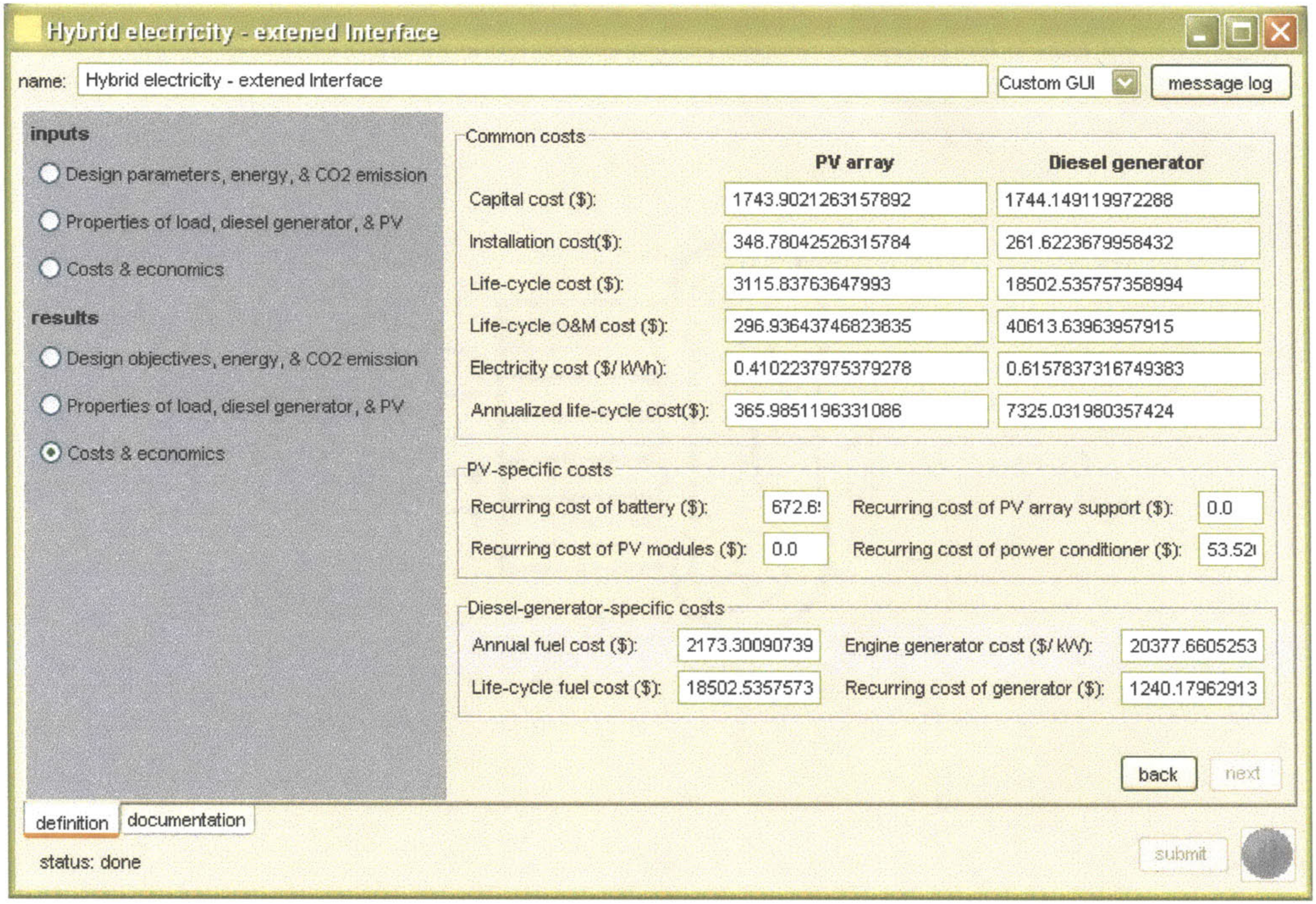
Fuel consumption rate (l/ kWh): 0.26099999

Engine oil change period (h): 150.0

Engine's operating lifetime (h): 10000.0

Annual engine oil change count: 58.44

status: done



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Common costs

	PV array	Diesel generator
Capital cost ($):	1743.9021263157892	1744.149119972288
Installation cost($):	348.78042526315784	261.6223679958432
Life-cycle cost ($):	3115.83763647993	18502.535757358994
Life-cycle O&M cost ($):	296.93643746823835	40613.63963957915
Electricity cost ($/ kWh):	0.4102237975379278	0.6157837316749383
Annualized life-cycle cost($):	365.9851196331086	7325.031980357424

PV-specific costs

Recurring cost of battery ($): 672.6
Recurring cost of PV array support ($): 0.0
Recurring cost of PV modules ($): 0.0
Recurring cost of power conditioner ($): 53.52

Diesel-generator-specific costs

Annual fuel cost ($): 2173.30090739
Engine generator cost ($/ kW): 20377.6605253
Life-cycle fuel cost ($): 18502.5357573
Recurring cost of generator ($): 1240.17962913

status: done