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| --- | --- |
|  |  |
| LCoE | Levelized Cost of Energy |
| NPC | Net Present Cost |
| LLP | Loss Of Load Probability |
| GUI | Graphical User Interface |
| UI | User Interface |
| DoD | Depth of Discharge |
| DST | Development Support Tool |
| LoL | Loss of Load |
| MSE | Micro and Small-scale Enterprises |
| PV | Photovoltaic |
| SoC | State of Charge |
| OeMeR | Operations, maintenance and replacement |
| OeM | Operation and maintenance |
|  |  |
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|  |  |

**Sammendrag**

I dag trenger fortsatt millioner av mennesker strøm, som regel i jordbruksommeråder i fattige regioner. Studier viser at den beste måten å realisere forsyning av disse menneskene, både økonomisk og for miljøet, er via microgrids, isolerte produksjonssystemer av strøm. Da microgrids er kompliserte, er det viktig å gjøre tilgjengelig verktøy slik at disse prosjektene har større sjanse for å iverksettes, og lykkes.

Dette prosjektet har som formal å utvikle og ferdigstille et utviklingsstøtteverktøy for microgrids der størrelse på solceller, batteri og ekonomiske projeksjoner skal beregnes gjennom simulasjoner. Det skal også være mulig å inkludere biomasse generasjonsalternativer i simuleringene.

Verktøyet skal være tilpasset lansering som open source, ha nøye dokumentasjon tilgjengelig på nett, og skal videre ha et brukergrensesnitt for å forbedre prosesser som testing og generell bruk. All koden er skrevet i matlab og har blitt implementert med generiske tilnærminger til problemstillinger som brukere står ovenfor, på denne måten kan utviklingsverktøyet brukes i de fleste kontekster uavhengig av detaljer i planlagte systemer. Koden er strukturert nøye, basert på publiserte studier av kode kvalitet, for å legge til rette for videre utvikling.

**Abstract**

Presently, millions of people are still without elevtrical power, most of which alocated in rural areas in poor regions. Studies show that the best way of supplying these people, both economically and environmentally, is through microgrids – islanded power generation systems. It is important to make available tools to help realize microgrid installments, so that these projects have a better chance of being initiated and successfully finished.

This projects puprose is to develop and finish the design of a ‘Development Support Tool’ for microgrids, where size of Photovoltaic panels, batteries and economic projections are calculated with help from simulations. It is possible to include biomass generation strategies in the simulations.

The tool is designed to be suited for open source publishing with a thorough documentation online and a user interface to improve processes such as testing and general use-cases. All the code is written in Matlab and has been implemented with generic approaches to problems that users are faced with, and in this way making the tool applicable to a wide range of microgrid contexts, independent of system details. The code has been structured meticulously based on published studies on code quality to facilitate continuing development.

**Preface**

Dedicated to Tord Are Meisterplass for being a warrior and generally awesome person.

In memory of Thomas Tveten.

I extend my deep gratitude for everyone who offered their support and encouragement. Especially my dear friends who inspired me to get a technical education and the friends I’ve made during my years in Trondheim, you have all challenged me a million times and continue to do so.

I must thank NTNU and its staff for all the opportunities I have been provided here. My supervisor Marta Molinas for dedicating her time to projects that can make the world a better place, to Stephano Mandelli and Håkon Duus for the inherited work.

Thanks to my large and small family for their continued love and support.

# : Introduction

## Background

The following sections are purposed to properly include the reader in the scope of this thesis. After the motivation comes sections meant to introduce necessary technologies and concepts. What role the technologies play in the thesis context is discussed in section 1.2 and 1.3.

### Motivation

The world’s population is growing, at the same time the life quality of the inhabitants is increasing. Combined, these two factors pose an unparalleled challenge for humanity as this will raise the demand on the global environment substantially. The International Energy Agency found that 1.3 billion people live without electricity, 80%, or more than 1.1 billion people out of these, live in rural areas where families mainly depend on small-scale agriculture to survive (International Energy Agency 2016). Renewable off-grid systems are the best option for rural electrification, this is shown by several analysis at local level. (Mandelli, et al. 2014)

Intellectual resources can be disproportionately expensive, putting up barriers for those wishing to make use of technological progress but with economic restrictions. Empowering those without the infrastructure and licensed intellectual property (IP) of western businesses is crucial if we want sustainable technology to be utilized seriously where it is needed (Chon 2006); not only out of humanitarian - but also environmental considerations.

Technologies concerning photovoltaic (PV), biomass power generation and batteries, are constantly evolving to more cost efficient and functional solutions, like that of Perovskite and new sulfur based cathode materials (Maximillian 2015). The required purchases to utilize this technology, is however somewhat complex. Component dimensions depend heavily on the operational conditions, and the variations in these conditions have large economic and practical implications, especially for those with meager resources.

Micro and small-scale enterprises (MSE), such as farmers or small business owners, would benefit greatly from a tool that can dimension versatile microgrid installations. This would supply the know-how needed to make safe investments; thorough projections also imply the possibility of producing concrete plans that can facilitate acquisition of financing, from either government or investors hence boosting development further.

### Terminology

#### CRF – Capital recovery factor

Capital recovery factor converts a present cost to a steady stream of partial payments given a number of payments *n*, and an interest between each payment, *r*.

#### LCoE – Levelized cost of energy

LCoE is what you pay for each kW supplied to the load, that actually reach the user.

CRF is necessary since we are making an annual analysis of the system. LCoE is therefore the annuity of the NPC divided by the kWh supplied each year.

#### LLP – Loss of load probability

Loss of load probability is the probability that a kW of power in the load profile will be unmet.

Understanding what affects this figure is important. Say that some days are cloudy and at the same time the power consumption goes up due to increased indoor activity or heaters, then some days are sure to lose power with high contribution to the LLP, but if this happens seldom then these days are unimportant and should have less meaning for the evaluated quality of the system

On the other hand, if the supply of power from solar panels just barely is unable to serve the load over long periods of time, the ratio off lost load to the load demand is then very small in the calculations, but in reality you still have a power shortage, meaning that the low percentage does not reflect the loss of utility.

One solution to this can be simply counting the down time of the system, instead of being concerned with the magnitudes. This is implemented in the current DST as a user output.

#### SoC – State of charge

State of charge is the ratio of energy charged to the maximum capacity of the battery.

#### DoD – Depth of discharge

The compliment of SoC

#### Irradiance

Irradiance is the gross watt per square meter from the sun. Precise data can usually be found on NASAs webpage. <https://eosweb.larc.nasa.gov/sse/>

### Open Source

Open-source is the practice of open process internet based development projects, where developers can make contributions to projects through reviewing existing code or adding new features. Open source will help keep software alive as it invites users to participate in increasing the quality of the software, this way the development will increase with the degree of distribution. Open source code is free for anyone to download under the creative commons license.

Open-source contributors have proved to work with a high level of expertise and commitment, they are highly motivated and work for free. Linux and Ubuntu are examples of software used by developers in high prestige corporations. Wikipedia has become the largest encyclopedia in history compiling information on nearly every subject of modern knowledge, also the result of a collective open source effort.

### Microgrids

A microgrid is subsystems of interconnected loads and distributed energy sources that are locally controlled. The microgrid can either be islanded or connected to the grid. This is associated with network operational benefits such as cost efficiency and voltage control. It will also enable the implementation to be more adapted to the local conditions and new technology (Berkeley Lab 2016).

Microgrids are complex, which often lead to increased investment costs that put up barriers for widespread use, they do however facilitate additional value streams that improve economic viability. (Stadler, et al. 2015). This thesis is concerned with making the complexity of the microgrids, more comprehensive, hence reducing the investment cost.

### Biomass Power Generation

In this paper, biomass power generation includes the sustainable combustion of biomass from either agriculture, municipal or household waste, or digestion of either. Sewage or livestock can also be digested to produce biogas.

#### Thermal Power Generation

Thermal power generation is the transition of thermal energy in steam to a turbine. The steam is heated by a boiler, which in turn is heated by a furnace or by solar focalization. Heating implies a startup delay depending on the furnace efficiency and the boiler size.

The steam quality measured in dryness has to be high, at least 90%, meaning only 10% water vapor, as any higher amount is likely to damage the turbine. The most efficient steam turbines require superheated steam of dryness 99.5%, which in turn require minimum leakage and high efficiency from the boiler and furnace. Solids in the water needs to be filtered out through a fine mesh. The process loses little water and so there is no need for a stable water source once sufficient filtered water is acquired.

Steam turbines does not usually require much maintenance and can have a 20 year life span without any extra costs. The boiler and pipes might need minor repairs, but these components are normally easily available and does not require special training to handle.

#### Producer Gas from Biomass Gasifier

Gasifiers are special furnaces that use incomplete combustion of biomass to produce ignitable gas, known as producer gas, for several types of generators. Producer gas consist of carbon monoxide and nitrogen, which is “scrubbed” from tar so that it may be used in either gas turbines, gas or diesel generators, the latter in combination with diesel. In any case there will be a startup delay when starting the combustion process.

The gasifiers are approximately the same size as the thermal power plants but the weight of the specialized components are combined much heavier. In the thermal power plant, only the steam turbine has to potentially be shipped and the remaining parts bought locally, meaning that shipping costs are much higher for a gasifier.

The generator can be replaced with several variations of locally available engines, the only required customization to off-the-shelf generators is to change the air intake to producer gas mixture ratio of 1:1. Producer gas therefore offer increased flexibility compared to the thermal power plant and potentially a longer plant life-span. The plant does require some special training to operate which can be supplied by manufacturer.

In conclusion, the producer gas solution provides more flexibility in generator choice, in exchange for a substantially higher investment cost, despite purchasing costs being quite similar.

#### Biogas from Anaerobic Digester

An anaerobic digester is simple to install and operate, and is available in any scale desired at a fair price. The digester utilize biomass, waste, sewage or either to produce biogas. Biogas is mainly methane and carbon-dioxide, but also contain hydrogen sulfide, water and siloxanes, which are considered contaminants. Methods for producing uncontaminated biogas and removing contaminations post-production are continuously being developed.

The biogas are best utilized in a combined heat and power (CHP) gas generator, where the spill heat is used for the digester. The startup time is equal to that of a gasoline generator and can be less than a minute.

The Intergovernmental Panel on Climate Change (IPCC) suggest that over a 100 year period, CH4 might contribute to trapping 34 times more heat in the atmosphere than CO2 (Alexander, et al. 2013), measures to counteract dissipation of methane should be taken seriously. Anaerobic digestion will reduce the CH4 emissions during storage (S.G 2005) and is then replaced by CO2 emissions at combustion, a lesser of two evils.

Using biomass from agriculture and waste will diminish the strain on the local-, in addition to the global environment. Biogas can replace wood for cooking, a predominant reason for deforestation in areas with high poverty, according to IEA 2.6 billion people still rely on traditional biomass for cooking (International Energy Agency 2013). Additionally, digested dung will reduce toxicity and odor which attract flies and rodents, creating a health hazard for rural populations (Sooch 2013).

Fossil fuels or reserve stocks of biogas can easily be stored at hand or purchased to completely replace the plant production, this enables for more operational resilience and the microgrid can be assigned to handle more vital tasks. Generally this resilience also implies a potential for purchasing lower losses of load when desired (Stadler, et al. 2015).

Digester solutions are more often subsidized than not, and purchase costs are usually quite low with high likelihood locally available parts. Economic aspects are hence much better than those of thermal power and producer gas plants.

On the other hand, a biogas digester requires much more infrastructure to run. The gas must be stored in special containers and the digester takes up space and the processed biomass must be removed. Larger operational costs are hence implied.

Production on biogas depends strongly on the quality of biomass and the digester, estimating the needed size for production is therefore something to be discussed with supplier, the digester itself is relatively cheap and making a larger digester does not imply a big price difference.

For comparison of the different biomass system purchase costs see table below.

Table 1: Some Rough Purchase-Price Indicators

|  |  |  |  |
| --- | --- | --- | --- |
| post | Thermal Power Plant | Producer Gas Gasifier | Biogas Digester |
| Full system w/grid tie price (dec 2015) | 40 000 $ | 40 500 $ | 20 000$ |
| Price Quote Source | Green Turbine | All Power Labs | alibaba.com and alberta.gov, rough estimate |
| Transportation Cost | low 55$-140$\*  + insurances up to 550$ | very high | very low |
| Notes | package weight 25 kg boiler locally available | package weight 693kg+70kg | typically locally available |

\* (DHL 2016)

## Problem Formulation

While the potential and utility of installing microgrids with different technologies is very large, the investment cost is higher than conventional installations because of the complexity in design. The planners are faced with choices where details have large economic consequences, which cannot be taken lightly, especially in poor rural areas of development countries where such installations are needed the most. We wish to facilitate understanding and information that brings safety to investments made in microgrids, this will have substantial both humanitarian and environmental consequences, given the amount of people in need of electricity. We will achieve this with a development support tool (DST) for mictrogrids.

The technologies we wish to exploit are basically any that are eco-friendly and economically feasible. We wish the tool to be easily built upon with new features and new technology as it becomes available. The DST finished in this thesis utilize that of PV, biomass generators and batteries.

To indicate what a user can expect from performance given an investment, simulations are necessary. The simulations will estimate the performance of a given system, but also how systems are worn over time, which will have large consequences on the operations and maintenance of the installation.

The product will be ready for shipping under the creative commons license, free for anyone to use. The development are intended for users and students to undertake, where both groups are encouraged to add features either from necessity while utilizing the DST or any other motivation.

The program follows a set of programming standards which allows for users and developers to inspect modules without understanding their context extensively, and also the program architecture without understanding how the modules work. The DST has a graphical user interface and detailed online documentation

### How does the Development Support Tool (DST) Work?

The DST is a tool for dimensioning microgrids in a flexible and comprehensive way. The user supplies a range of component sizes of which performance and economic consequence is calculated. These calculations are based on simulations of systems with the different components in operation. The user will also have to supply economic and performance parameters of the intended purchase, including data on the context of which the system will operate, this always includes a load profile. The system finds the best solutions of certain characteristics, such as loss of load probabilities, and produce graphs and key figures to describe the performance and costs associated with the resulting systems to the user.

## Literature Survey and Previous Work

### External Research

There has been several papers on dimensioning microgrids. Some are considered mostly with macroeconomic aspects and high complexity (Hawkes 2009), some with technical considerations to control (CHEN, et al. 2013) and others using IP software such as Homer (Hafez og Bhattacharaya 2012). The common denominator is however that the software used in the papers either cost money or are unavailable to the public. In addition, the intended reader of these studies are other scientist in the same field, the utility for the average MSE is therefore nonexistent

### Existing tools

There are however tools on the market with capability of performing the analysis that we propose, these are however with limitations and licenses. An extensive list can be found in the literature review of (Connoly, Mathiesen og Leahy 2010) dated 2010 the paper does not mention BlueSol, PVSyst and RAPSim. Although somewhat outdated, it supplies a curriculum of different type-tools and respective core functionalities.

Studies on the functionality and limitations of contemporary tools has been carried out before at NTNU by Daniele Sakepa (Sakepa 2015) and Anne Lozé (Lozé 2015), the following section will try to briefly summarize to draw the distinction of our DST.

#### HOMER

Hybrid Optimization of Multiple Energy Resources (HOMER) is the most popular choice. The tool performs excellent economic analysis and simulations, and demands similar economic parameters as our DST, and additionally a database of products with parameter-sets automatically defined, inclusion of this feature is discussed in further work.

Flexibility is lacking in step sizes of PV and batteries. The step sizes are predefined and does not allow refinement of the solution space to better meet poorly funded users’ needs where financial margins count more.

The tool does not support budget constrained-searches, described as Top-Down analysis in Connolly et.al. The development of this feature is discussed in section 3.4.2 as further work. The current DST has this problematic partially solved through the ‘Simulations Overview’ plot described in section 2.3.3.1.

Supports biomass generation in the microgrid as one of the core functionalities. The tool does not, however allow for detailed operation of the biomass system as inputs to simulations.

Some enigmatic behavior is described by Lozé, the claims are that battery discharge does not happen despite of sufficient capacity, and that different results is produced despite identical inputs. The occurrences are mentioned without plots or data associated for inspection. Concepts such as power-energy ratio (the discharge capacity given spesific charge levels) and the stochastic features of HOMER can explain these behaviors. Considering the existing integrity of HOMER and given the frailty of these posed enigmas, the notion should be ignored.

#### BlueSol

Not extensively tested in the reports due to price. The price is equal to the purchase of 1 kW of PV panels which is unacceptable in a small scale setting. The trial version is has too few features to produce satisfactory results.

Keeps a very large database but is then restricted to these choices. There is no user specific data inputs and if a user cannot find a set of choices that matches their use-case, the tool becomes imprecise and quite useless. Does not include contribution from secondary sources such as biomass generators.

#### RETScreen

A free-of-charge excel based ‘Clean Energy Management’ tool, mainly focusing on economics and not including simulations and detailed performance data, reducing computational time significantly. The simulation feature is important to our users as they need to understand the practical implications of how a system operates.

As proposed by Connolly et.al, RETScreens main function is intended to justify clean energy investments compared to conventional power generation, and not necessarily to prospect installations in detail. It does however consider parallel generation strategies such as biomass power generation.

#### PVSyst

Mainly a highly detailed PV installation optimization tool. Like RETScreen, PVSyst does not seem to produce operational simulations with hourly load data, which are important in our specifications. Instead the tool makes its own load data through user entering the number of domestic appliances, lamps etc. This makes the tool further unsuitable if the user operates a farm, which have machines and appliances that do not translate to household appliances.

#### RAPSim

A review is included in the thesis of Håkon Duus of this tool which aims to be an open-source microgrid design tool. It does not work with dimensioning and economic analysis which is paramount to our functionality. This tool could however be very useful to complement the use of our DST.

#### Summarized, what’s Generally Lacking

With exceptions to RETScreen and RAPSim, all the tools mentioned introduce increased costs for the user. The fees might be acceptable for a complete DST purchase, but as our argument dictates, they all have different short-comings, not justifying the investments.

Another quality in our DST is flexibility. As our tool is open-source and modularized, any kind of feature can be developed and used with the existing code, there are no restrictions. A benefit that also comes with this is complete transparency of calculation process. If the user has any doubts or special cases previously unconceived in the design, the source-code is easily accessible for inspection.

With varying competence among users, the proposed DST is more adaptable to different contexts. One might only want to use the parameter inputs and read the analysis outputs, or maybe change a module without knowing anything else that is going on, the tool should support all ranges of use.

### Past Work on the DST (logplot.m)

The DST was initially developed and described by Stephano Mandelli and further developed by Håkon Duus and Jemjin Scheen. The program was inherited in a single Matlab .m file named logplot.m which can be seen in Appendix B. The DST is currently too large to enclose as paper, but the entire program can be downloaded or inspected easily, follow the instructions in Appendix A

The functionality of the DST in logplot.m, is explained here. There are three stages of calculations, namely the simulations, the economic analysis and the search for optimal solutions.

#### Producing Simulations

Different combinations of PV and battery sizes are “tested” in the simulations step. Given a range of PV and battery sizes, estimations or measurements of a load profile, irradiation data and ambience temperature data, the interaction between these data sets are simulated. There are also scalar parameters affecting the physical performance of the components, and for the conditions under which the system will operate. This means that every combination of PV and battery sizes will each have a full timeline simulation of absorbing energy from the sun, serving the load, charging and discharging the battery. This results in a computation complexity of, given a

The system works as follows: for every PV size, an array of absorbed power is calculated, if the absorbed power (with losses) are sufficient to cover the load demand, the surplus power will charge the battery (for current battery size). If the absorbed power is insufficient, the battery will discharge. If there is insufficient power available, or if the load demand fluctuate too much, there will be a loss of load.

For every discharge cycle, the DoD is used to calculate how large fraction of the battery lifetime is consumed. This calculation stems from a function called cycles\_to\_failure. This is a fitted function to the battery “cycles to failure” vs. “depth of discharge” characteristics, proposed by the battery manufacturer. This must be replaced or verified as relevant to the implementation by the user, if precision is desired.

#### Conducting Economic Analysis

The economic analysis will take each combination of PV and battery, which now have timelines of simulation results associated with them, and produce economical calculations. The outputs are mainly based on calculations on the input parameters, and not simulation outputs. The exception is the battery replacements needed and LCoE (the cost for each kWh supplied).

The sum of partial cycles used is not an hourly data set, it’s a fraction of the battery lifetime consumed during simulation time. Replacing batteries are very costly, and therefore the cycles\_to\_failure function has a major impact on the economic results.

#### Finding Optimal Solutions

The last step is finding some simulations that display the desired dimensions for performance and the optimal cost amongst these. The user defines a range of LLP, and an accepted deviation from the given LLP values. For each LLP in this range, if a match is found in the simulation outputs it will be listed as an optimal solution. Usually, there are several matches. The simulation with the lowest NPC will be chosen as the optimal solution among these.

The inherited code is displayed in Appendix B. The code of the tool is located within one file. This implies that the user will have to run the entire file, regardless of the desired functionality. The lack of modularity comes from the intertwined functionality, but also a practice of overwriting variables during iterations.

#### A Use-Case for Logplot.m

1. **Parameter Input**

The user needs to find the parameters that affect the economic and physical conditions for his planned purchase. Since both technology and economic conditions change as time goes by, any result produced by the DST will be useless if the parameters are not up-to-date.

The parameters important to change for the user are: batt\_ratio, coeff\_cost\_BoSeI. coeff\_T\_pow, costBatt\_coef\_b, costBatt\_coeff\_a, costINV, costOeM\_spec, costPV, eff\_BoS, eff\_char, eff\_disch, eff\_inv, irr, irr\_nom, Load, LT, max\_batt, max\_PV, max\_y\_repl, min\_batt, min\_PV, n\_batt, n\_PV, r\_int, SoC\_min, SoC\_start, step\_batt, step\_PV, T\_amb, T\_nom, T\_ref, x\_llp and the function cycles\_to\_failure.

These parameters are hardcoded somewhere in the script. It depends on the users understanding of the different parameters, based on the comments that might accompany them and the parameter name, whether they should be researched and changed or not. There is no clear distinction between calculation variables and constant parameters.

1. **Simulation Scope Input**

The size of the components in the battery is defined by the variables min\_batt, max\_batt, step\_batt, min\_PV, max\_PV and step\_PV. This defines the simulation space. There will be n\_batt, n\_PV simulations based on these variables. If the user cannot find sizes in the scale of the load demand with appropriate LLP or NPC, an expansion of this range is necessary. If the user is interested in smaller variations between alternatives, for more detailed search, a smaller range and smaller step is necessary.

1. **Run Simulation**

The simulation will run through all the PV and battery combinations. Calculating a LoL matrix LL. The calculation complexity is. The stages for simulation, economic analysis and optimum search are all executed within this step.

* 1. Plotting and Accessing Calculation Data

When you know what combination of PV and battery you wish to inspect, it must be hard-coded into the simulations part in order to access the data and make the necessary plots. In order to know what results occur during a simulation, a breakpoint must be inserted in order to view the data-set points before they are overwritten.

1. **Solution Space Inspection/Refinement**

The calculations that are not used later in the code is overwritten in every iteration, the user is unable to see exactly what has happened during the simulations. After the simulation you will be able to access the optimal values in the MA\_opt\_norm\_bhut\_jun\_10\_16 output matrix. These will tell you which PV/battery combinations in the predefined LLP range were found as optimal. The measure of quality is given by LLP, NPC and LCoE. At this stage the user knows better what range to examine closer based on these. Return to step 2-4 to inspect values with break points, and hardcode what solutions to plot. Repeat until the solution is satisfactory based on the LLP, NPC and LCoE values.

## The Contribution of this Thesis

Starting from logplot.m, a proto-product has taken form. The code has moved from being a single script with many hard-code features to becoming a collection of interchangeable modules, help functions and GUI functions. The work has been rewritten by strict coding standards founded on research, and bugs have been fixed. The code is more flexible with respect to its structure and readability, but also with respect to data inputs which can now span several years without having to modify the code. The program operates on any operating system without any modification having to be made.

Several new biomass modules has been added, these allows for any biomass power generation system to be part of the simulations. The biomass state machine takes on a generic approach that enables it to simulate the behavior of autonomous, or manually operated systems. This will help bring down the LCoE for the user, and facilitates additional flexibility and security in the microgrid installation.

The new DST is accompanied by a powerful GUI that speeds up the use of the system significantly. The GUI additionally facilitates an understanding of the intersection between user and program, where this earlier was unclear.

The DST\_platform GUI enables execution of simulations in different stages and in different modes, documentation look-up and solution-space inspection is quickly produced by mouse clicks. The entire set of parameters necessary to run the program is input through the GUI, these input sets can be saved as presets. This allows the user to cycle quickly between presets, to save, delete or update them when needed when comparing different solutions or working with several configurations.

The second part of the DST GUI is the solution\_explorer. This GUI enables exploration of solutions produced from simulations, economic analysis and the optimum search stages. By pressing buttons the user can display several plots, some new and some from the logplot.m script, and a great deal of key information only calculated in the new DST. The outputs can easily be put aside for comparison with other solutions or new parameters.

The DST has a detailed online reference guide which are equivalent to 32 A4 pages. The online documentation is carefully written to express the meaning of each parameter and output of the DST, it also explains the functionality of each module, help function and GUI which combined amount to 23 Matlab files.

The new DST is not only functional but manageable, and each iteration has been made with the project successors in mind to ensure the vitality of this project.

## Objectives

The main objectives of this master’s thesis are:

1. To design and implement a powerful DST for microgrids, flexible to both diverse microgrid contexts and user needs.
   1. Strict code quality standards.
   2. A new biomass generation module for simulations.
   3. Elaborate GUIs that produce a wide variety of outputs.
2. To thoroughly document and ensure accessibility for later contributors.

## Approach

### Rewriting and reorganizing existing code

The first step in this thesis was changing all the names in logplot.m to fit some quality standards. The changes were based on studies and personal experience in using the code, it had been difficult for both the author and other collaborators. The goal was to have identifier names which could work as documentation in themselves so that a line of code could be read completely out of context, and still make sense.

Then the code was split into modules. Initially this meant 3 large modules for each analysis step described above, namely: simulations, economic analysis and optimal search. The outputs and inputs organized into classes, and a large amount of variables overwritten in the computations in logplot.m were stored as large matrices. Some plotting functionality and cycles\_to\_failure was also placed in modules. The reorganized code was tested for performance and correctness and some erroneous calculations were corrected.

#### Immediate Benefits of increased Code Quality

The code can now be tested in parts without embarking on large computations each time, plots can be produced instantly from the stored matrices of outputs. Calculation steps can be repeated with arbitrarily large inputs. This speeds up interaction with - and development of the code tremendously.

Questions about functionality is more frequently answered without looking in the code for comments that explain the variables concerned. Errors stand out as they break the logical narrative that results from these standards.

#### Long-term Benefits of increased Code Quality

A philosophy of open-source is that given enough eyes, all bugs are shallow. This is to some degree true, but some bugs can never be shallow as they are part of the specification or macro structure; these are called upstream errors. Upstream errors are 10-100 times more resource demanding to fix than downstream bugs (shallow bugs) according to (Bollinger, et al. 1999).

Up-stream errors cannot easily be detected and fixed unless the code quality is on a certain level where the modularity and readability express specifications and communications clearly. Open-source needs to be “rigorously modular, self-contained, and self-explanatory”.

While good closed-source organizations are of course aware of the benefits of good modularity, only open-source methods provide the kinds of individual incentives though which such practices can easily flourish and evolve over time. They also provide a warning about efforts such as Netscape’s Mozilla that attempt to move weakly modularized proprietary code into open source (Bollinger, et al. 1999)

It has been shown empirically that there are significant associations between flawed identifiers and code quality issues though a static analysis tool called FindBugs. (Butler, et al. 2009). FindBugs recognize ‘bug patterns’ in java byte code. Mentioned ‘bug patterns’ result in aberrant runtime behavior and some concern the maintainability of code.

The bottom line is that open source projects are highly unlikely to have any success if there aren’t some ground rules, much like that of a buildings foundations.

### Creating a user interface

A GUI was created with Matlab. The GUI code files are very large but contains simple functionality. Elements and their properties are defined with Matlab functions, the implementation looks much like that of CSS.

The dst\_platform.m GUI was made to handle the inputs, simulation and calculation part of the DST, and the solution\_explorer.m was made to handle the outputs to the user.

The GUI enables agile testing of the DST, results can be reproduced through the presets and plots and important key outputs can be compared quickly by producing several output windows. The GUI is also a proto-program for the shipped DST and aims to communicate clearly to users.

### Simulating a biomass power system

The SAPV simulation module was modified to support the operation of a biomass generation system. The operation is realized by a state machine which determines what operation mode is currently running, the different states determine how long the generator should run each hour. The inputs were chosen to be as generic as possible to support any kind of biomass power production that can be implemented whether it runs automatically or is operated by humans, or whether it is powered by a gas generator or a steam turbine

#### Why is the Biomass Feature important?

The daily variation of irradiance and load demand can vary so much that dimensioning a SAPV power plant, without large amounts of overproduced power is impossible. Variations can be extreme as a result of negative correlation between load and irradiation, this can for example occur in winter if irradiation decrease and simultaneously load demand increase with use of electric heating. The variations might affect load or irradiation separately and sufficiently to result in large amounts of overproduction because the power plant has to be dimensioned to handle these cases.

Overproduced power occurs when the battery is fully charged and there is more available power after load saturation. Overproduction can be considered a loss of money, when financing supply of load in such a system, you also pay for the overproduction, which is suboptimal. Meaning that a reduction of the loss of load probability (LLP) becomes much more expensive in terms of levelized cost of energy (LCoE) once overproduction starts occurring in a system.

Biomass power generation can solve dimensioning problems because it can be stored and used when it is needed. Biomass can also be bought and sold, and provides a flexibility and operational resilience that is unavailable in a SAPV plant. Operational resilience is important because it makes the microgrid eligible to handle tasks that have harder demands on operational reliability, such as providing clean drinking water and santitation.

The benefit of installing a biomass power system has many aspects, there are many factors that might justify or complicate the installation such as infrastructure, price of biomass or fuel, the quality and variation of supply etc. The availability of biomass might naturally become larger as the power demand increases, for example when harvesting and processing crops, but this is not helpful if the material needs to dry first, then the biomass might need to be stored for when the demand increase at a later time if it can’t be sold.

### Documentation

Documentation was written in HTML and published online. The documentation is written in very simple code so that editing and adding to the HTML code require a minimal of programming skills. The code was made to be easily searched or browsed and can be accessed from a phone or computer.

This is highly important as any user or developer will have to look for explanations within the code if no online reference is available. This does not only take time, but the code comments risk disappearing during new iterations of the software. The survivability of the DST is completely dependent on good and available documentation.

## Limitations

#### Time

The project involves a large amount of tasks to be done. This means that time becomes an issue. The functionality of features can be fairly simple, but considering the quality of work with successors in mind, testing and documenting and fitting the feature into the tool takes time. Making the mathematical implementation a smaller part of the total work when finishing a module.

#### Synchronized work

Updated modules from earlier collaborators has been hard to acquire, hence some potential synergy was lost. The new standards of implementation should amend this as the code is not interconnected the same way so that features can be developed in parallel.

#### Training Sets of Data

Tests have not extended much past the data provided by the predecessors. Training sets are not very important for most of the implementations done in this thesis. There is however the testing of the biomass system. The training set provided from Bhutan is a system which has high utility from a secondary power source, hence the testing was satisfactory without acquiring additional data.

#### Microgrid Technical insight

Detailed technical understanding of microgrids is not part of the author’s field of study. The author has a background in technical cybernetics and is therefore familiar with simulations and automation and program development. This has not proven a problem for the tasks.

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## Structure of the Report

The rest of this thesis mainly consist of the methodology and corresponding discussion of what has been done. During the methodology part each successful addition to the DST is explained in detail. Each chapter aims to present its general approach and then the details of the implementation. The results of finished implementations follow the implementation details.

After all modules are discussed, a use case of the tool is presented in the last chapter with the discussion and conclusion. The use case will try to give an understanding of how the finished product can be used.

The source codes are digitally available because they are too large for the paper format. The explanation on how to get the digital resources are in the Appendixes.

# : Methodology

## Code Review and Redesign

Logplot.m was difficult to use and develop from a number of reasons. The formatting made the code hard to read, there were no naming convention to help developers to understand the script functionality and the script had no modularity to ensure safe development, testability and encapsulation of variables.

It was observed that collaborators did not understand most of the functionality in logplot.m, not in a macro or micro perspective, this lead to downstream and upstream errors as the script was developed. The state of logplot.m also made development time-demanding, as each collaborator had to understand the entire script in order to confidently and safely make changes.

The restructuring of logplot.m to the new DST follows a union of several code quality standards, those of Richard Johnson (Johnson 2002) and (Butler, et al. 2009) set the main guidelines for naming convention, and the quality standards of the former and (Martin 2009) for macro architecture.

### Naming Conventions, Commenting and Formatting

The rewritten DST naming convention follows the quality standards from (Butler, et al. 2009). These metrics were found to be correlated with error frequency in in 8 established open source Java applications libraries. The different measures of quality is found in Table 2: Code Quality Metrics.

Some metrics can benefit from an explanation. The ‘Capitalization Anomaly’ states that regardless of the abbreviation, the capitalization should only be used as a substitute for white-space between words. The ‘Identifier Encoding’ metric state that the type, such as integer, double or string, should not be used as a Hungarian-style prefix, whereas the *kind* can be indicated this way. The detailed reason is explained in (Spolsky 2005).

Table 2: Code Quality Metrics (Butler, et al. 2009)

|  |  |  |
| --- | --- | --- |
| Name | Description | Example of flawed identifier(s) |
| Capitalization Anomaly | Identifiers should be appropriately capitalized | HTMLEditorKit, pagecounter |
| Consecutive Underscores | Consecutive underscores should not be used in identifier names | foo\_\_bar |
| Dictionary Words | Identifier names should be composed of words found in the dictionary and abbreviations, and acronyms that are more commonly used than the unabbreviated form. | strlen |
| Excessive Words | Identifier names should be composed of no more than four words or abbreviations | floatToRawIntBits() |
| Enumeration Identifier Declaration Order | Unless there are compelling and obvious reasons otherwise, enumeration constants should be declared in alphabetical order | enum Card {ACE, EIGHT, FIVE, FOUR, JACK, KING ...} |
| External Underscores | Identifiers should not have either leading or trailing underscores. | \_foo\_ |
| Identifier Encoding | Type information should not be encoded in identifier names using Hungarian notation or similar | int iCount; |
| Long Identifier Name | Long identifier names should be avoided where possible | getPolicyQualifiersRejected |
| Naming Convention Anomaly | Identifiers should not consist of non-standard mixes of upper and lower case characters. | FOO\_bar |
| Number of Words | Identifiers should be composed of between two and four words. | ArrayOutOfBoundsException, name |
| Numeric Identifier Name | Identifiers should not be composed entirely of numeric words or numbers | FORTY\_TWO |
| Short Identifier Name | Identifiers should not consist of fewer than eight characters, with the exception of: c, d, e, g, i, in, inOut, j, k, m, n, o, out, t, x, y, z | name |

The quality measures from Table 2: Code Quality Metrics are sometimes conflicting, and some trade-off has to be accepted. The priority of the metrics in the DST rewrite are determined by the experience that was made when discussing the script with collaborators, and from the personal experience of working with the tool.

There is sometimes a conflict between the metric pairs of ‘Dictionary Words’ and ‘Naming Convention Anomaly’ opposed to ‘Number of Words’ and ‘Long Identifier Name’. Meaning that some dictionary words or common abbreviations are not available for simplifying the variable name without diminishing the self-explaining property of the longer name. In these cases, ‘Dictionary Words’ are prioritized because they maintain the naming convention that every line should be as self-explaining as possible.

My argument is that the DST does not usually make very complex calculations, such as numeric estimates, discretization or recursions. The consequence is a simple program flow, where the program-counter moves predictably. When the DST makes calculations, it is usually the theoretical equations that make the code complex. This results in single line calculations that can be understood alone, and is not depending on a larger logical architecture. This relieves the need of a compactly expressed code, and makes the use of ‘Dictionary Words’ a higher priority. This has a self-documenting effect, the code has a narrative that explain its functionality. There is however, few exceptions where the variable name is longer than 4 words in the rewrite (excluded class prefix).

The following conversion of names were applied to the DST. All variables, except those used temporarily in functions, are associated with a class. The full class names are prefixing the variables in the table below.

Table 3: the Complete List of Variable Name Changes in Rewritten DST

|  |  |
| --- | --- |
| Names | |
| Logplot.m | After Rewrite |
| batt\_balance | SimulationOutputs.neededBattOutputKw\*\* |
| batt\_balance | SimulationOutputs.neededBattOutputKw\*\*\* |
| batt\_i | jBatt |
| batt\_ratio | BatteryParameters.powerEnergyRatio |
| budget | EconomicParameters.budget |
| coeff\_cost\_BoSeI | EconomicParameters.installBalanceOfSystemCost |
| coeff\_T\_pow | PvParameters.powerDearteDueTemperature |
| costBatt\_coef\_b | EconomicParameters.battCostFixed |
| costBatt\_coeff\_a | EconomicParameters.battCostKwh |
| costBatt\_tot | EconomicAnalysisOutputs.battCostTot\*\* |
| costBoSeI\_tot | EconomicAnalysisOutputs.installBalanceOfSystemTotCost |
| costINV | EconomicParameters.inverterCostKw |
| costINV\_tot | EconomicAnalysisOutputs.inverterCostTot |
| costOeM | operationMaintenanceCost |
| costOeM\_spec | EconomicParameters.operationMaintenanceCostKw |
| costPV | EconomicParameters.pvCostKw |
| CRF | EconomicAnalysisOutputs.capitalRecoveryFactor |
| cycles\_failure | SimulationOutputs.sumPartialCyclesUsed\*\* |
| Den\_rainflow | nMaxPartialCycles |
| DoD | depthOfDischarge |
| eff\_BoS | EconomicParameters.balanceOfSystem |
| eff\_cell | cellEfficiency |
| eff\_char | BatteryParameters.chargingEfficiency |
| eff\_disch | BatteryParameters.dischargingEfficiency |
| eff\_inv | InverterParameters.efficiency |
| ELPV | SimulationOutputs.pvPowerAbsorbedUnused |
| EPV | (deprecated) |
| filename | (deprecated) |
| flow\_from\_batt | SimulationOutputs.battOutputKw\*\* |
| IC | EconomicAnalysisOutput.investmentCost |
| irr | SimulationInputData.irradiation |
| irr\_nom | PvParameters.nominalIrradiation |
| LCoE | EconomicAnalysisOutputs.levelizedCostOfEnergy |
| LL | SimulationOutputs.lossOfLoad |
| LLP | SimulationOutputs.lossOfLoadProbability |
| Load | SimulationInputData.load |
| LT | EconomicParameters.plantLifetimeYears |
| MA\_opt\_norm\_bhut\_jun15\_20\_10(1) | OptimalSolutions.lossOfLoadProbabilities |
| MA\_opt\_norm\_bhut\_jun15\_20\_10(2) | OptimalSolutions..netPresentCosts |
| MA\_opt\_norm\_bhut\_jun15\_20\_10(3) | OptimalSolutions.pvKw |
| MA\_opt\_norm\_bhut\_jun15\_20\_10(4) | OptimalSolutions.battKwh |
| MA\_opt\_norm\_bhut\_jun15\_20\_10(5) | OptimalSolutions.levelizedCostsOfEnergy |
| MA\_opt\_norm\_bhut\_jun15\_20\_10(6) | OptimalSolutions.investmentCosts |
| max\_batt | SimulationParameters.battStopKwh |
| max\_PV | SimulationParameters.pvStopKw |
| max\_y\_repl | BatteryParameters.maxOperationalYears |
| min\_batt | SimulationParameters.battStartKwh |
| min\_PV | SimulationParameters.pvStartKw |
| n\_batt | SimulationParameters.nBattSteps |
| n\_PV | SimulationParameters.nPvSteps |
| NPC | EconomicAnalysisOutputs.netPresentCost |
| num\_batt | EconomicAnalysisOutput.nBattEmployed |
| P\_pv | SimulationOutputs.pvPowerAbsorbed\*\*\*\* |
| peak | loadPeakKw |
| Pow\_max | battMaxPowerFlow |
| PV\_i | iPv |
| Pvpower\_i | iPvKw |
| r\_int | EconomicParameters.interestRate |
| SoC | SimulationOutputs.stateOfCharge\*\* |
| SoC\_min | BatteryParameters.minStateOfCharge |
| SoC\_start | BatteryParameters.initialStateOfCharge |
| step\_batt | SimulationParameters.battStepKwh |
| step\_PV | SimulationParameters.pvStepKw |
| T\_amb | SimulationInputData.temperatureC |
| T\_cell | pvTemperatureC |
| T\_nom | PvParameters.nominalCellTemperatureC |
| T\_ref | PvParameters.nominalAmbientTemperatureC |
| total\_loss\_load | SimulationOutputs.lossOfLoadTot\*\* |
| x\_llp | SimulationParameters.llpSearchTargets |
| YC | EconomicAnalysisOutput.operationMaintenanceReplacementCost\*\* |
| years\_to\_go\_batt | battOperationalYears |
| Stored for after-simulation inspections in the rewritten DST | |
| \* Hourly data points are now stored in this variable | |
| \*\* PV and battery combination data points are now stored in this variable | |
| \*\*\* Both time and PV/battery combinations are now stored in this variable. | |
| \*\*\*\* Time and PV iterations are now stored in this variable | |

The unit of variables is included in some names, in order to easily detect errors when writing the code. When the unit of the variable is obvious, for example when discussing power or load, the unit is implicit and can be excluded.

The variables iPv and jBatt are important to notice. During simulation we have for loops for PV iPv = pvStartKw : pvStepKw : pvStopKw, for battery jBatt = battStartKwh : battStepKwh : battStopKwh, and time t = 1 : nHours. When accessing data points later we use the same variable name as a place holder. Meaning that if we have a pvStartKw = 100 and battStartKw = 100, the simulation outputs for LoL can be accessed as SimOut.lossOfLoad(:,1,1), here iPv = 1, and jBatt = 1. This way of referring to simulations is recurring in the rewritten DST.

#### Classes in the rewritten DST

Classes are the way the rewritten DST store variables in between functions and encapsulations, this has some great advantages. Classes allow for generation of variables automatically at initiation, hiding this repeated functionality from the user. The class SimulationInputData will for example only need the names of the files, and the folder name containing them to initiate the class. The result is a class containing all the data sets, variables for the length of the time series, and it will also generate warnings when the data-sets are of different lengths, and need to be preprocessed. This is all independent of which OS or computer you are currently using. The SimulationInputData constructor is displayed in

Figure 2:1.

A class implementation will make prevent assignments and accesses of variables that are not predefined for the class. For example if you attempt SimData.x Matlab will return: “The class SimulationInputData has no property or method named 'x'”. The class will also make passing of parameters to functions much less time demanding. If you need simulation parameters for a function, you can simply pass the simulation parameters all in one class. This allows for higher development agility and effective encapsulation of variables. As seen in

Lastly, the class will make the origin of the variables explicit, meaning that there is no question of what is meant by BatteryParameters.chargingEfficiency. This will assist the comprehension of the code.

A negative consequence is that the classes make variable names longer. These are however shortened in the different functions as they are passed. For example BatteryParameters.chargingEfficiency will typically be written BattParam.chargingEfficiency. This is ok because the number of classes are comprehensibly few and it contains its own full name as the type name.



Figure 2:1 The SimulationInputData constructor function

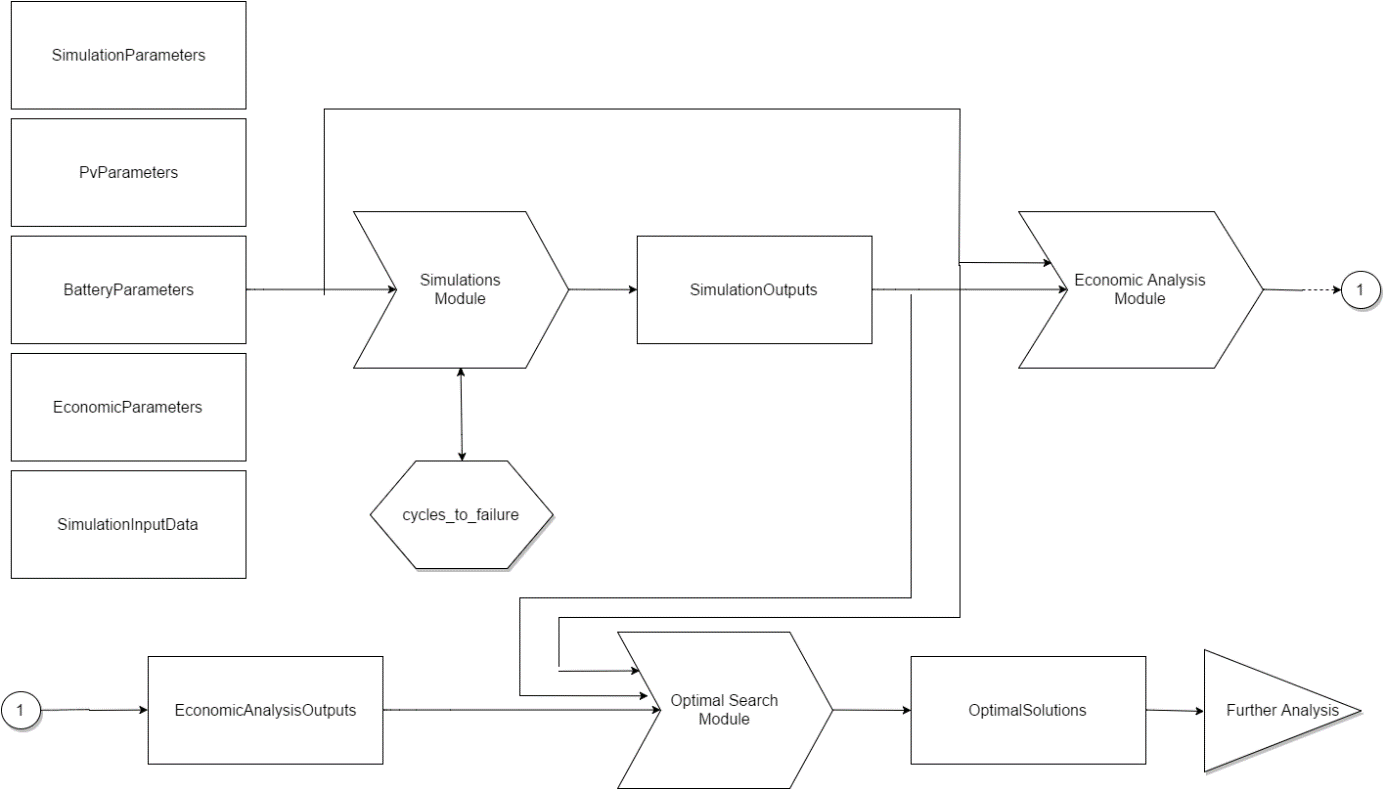


Figure 2:2: Class and Module Diagram

The classes enter the workspace when displayed in a rectangle.

### Modularization and Encapsulation

Encapsulation basically means that variables are restricted to their scope, they are not available from other functions and they are not stored when the scope has terminated. This will protect variables from unwanted access or interference, which results in a safer implementation. In the rewritten DST, encapsulation is mainly used to keep the workspace clean. When entering a function in Matlab, the variables that are passed to the function will be copied. The only calculations that comes out of a function is therefore the output variable of the function. This way, all variables that are irrelevant outside the function, are deleted.

Each module has an associated output class in the rewritten DST. The result is a workspace with only input and output classes (See Figure 2:2: Class and Module Diagram). This defines a clear intersection between modules. This also means that modules can be used in any order desired, or even used inside each other. A single simulation can be called simply by restricting the simulation parameters, or the plotting function can be repeated multiple times with different solutions.

This configuration allows for agile development and testing, as modules can be tested or replaced quickly without changing the rest of the code. If you wish to plot a solution, it will be enough to pass one or two classes as arguments to the plotting function. If you wish to modify an existing module, it can simply be copied and modified as desired without losing the previous functionality.

The modularization in the rewritten DST is based on the principle that one thing should be done at a time. It’s been said about quality code that it “does one thing well” (Martin 2009), this cannot be followed too strictly in this Matlab implementation. The reason being that the data-sets are too large to continuously pass between functions. Function calls in Matlab are ‘call by value’, meaning that a variable passed to a function is copied to the function scope. The potential memory consumption and computation overhead while doing this, could affect the development and testing flow. Hence, further modularization is reserved for a python implementation, where variables are pointers and ‘call by reference’ is default behavior.

### Formatting

Due to increased length in variable names, the readability can seem ‘cluttered’. The DST does however perform very straight forward arithmetic operations which are readable when aligned in columns. The equations are aligned by the operators as seen in Figure 2:3. The idea is that the user are accustomed to seeing the equations in this form, so the predictability of the format will remove ambivalence and doubts while speeding up equation comprehension. This is introduced because of the wide formatting native to Matlab and the increased length of variable names in the rewritten DST. This way the user can read the script without scrolling horizontally. This format might be unnecessary for readability in later versions, as the Matlab editor use a wide font and is unable to zoom out.



Figure 2:3Rewritten DST formatting example

### Evaluation of Finished Rewrite

In order to make a quantitative comparison of the rewrite and the original code, the bugs from the original DST was replicated in the rewritten DST. This way the changes in architecture is isolated and will produce the exact same data, if the implementation is correct. The relevant module is only Economic Analysis, the replicated module is named bugged\_economic\_analysis and prints a warning when run.

#### Correctness

Comparison of different outputs is used to prove maintained correctness. The function isequal(A,B) will compare every element in two matrices, and returns true (1) if the matrices are identical, and false (0) if there are one or more element with any kind of difference.

Given an input with large span and high resolution, there will be enough data points to safely state that the new implementation conserve the functionality from the old. We assume that the probabilities, the probability that a data point is equal despite an erroneous implementation, are independent. We also assume that these probabilities are independent of each other, and if they should be independent, the implementation would be correct. The probability of two matrices instead of data-points being equal, can then be described as follows.

One last assumption is that the average is not larger 50%. We wish to be at least 99.999% sure that our implementation is correct. We will use this assumption to state that consecutive correct answers despite of a wrong implementation is, and consequently the minimum required number of data points are:

For one time series in the DST we have 8760 data points in hours, which alone is sufficient to ensure correctness, but only for the modules that utilize the entire time series. When we evaluate the modules with lesser complexity, the data points decrease, therefore we need more complexity than one time series for testing the entire DST functionality.

Table 4: Complexity and output source of compared simulation pair outputs

|  |  |
| --- | --- |
| Variable Names | |
| Before Rewrite | After Rewrite | Module | n Data Points |
| SoC | stateOfCharge | sapv\_plant\_simulation |  |
| LL | lossOfLoad | sapv\_plant\_simulation |  |
| NPC | netPresentCost | economic\_analysis |  |
| LCoE | levelizedCostOfEnergy | economic\_analysis |  |
| MA\_opt\_norm\_bhut\_jun15\_20\_10(:,1) | lossOfLoadProbabilities | llp\_constrained\_optimum |  |
| MA\_opt\_norm\_bhut\_jun15\_20\_10(:,3:4) | [pvKw, battKwh] | llp\_constrained\_optimum |  |

In the rewritten DST, the calculations are executed in modules that pass parameters between them. These are placed in three classes that describe the key outputs of each module. Logplot.m is rewritten so that it saves more variables to workspace, we can now compare with the rewritten DST.

Given the validity of the coarse calculations above, we assume more than 99.99% certainty that correct calculations are a result of a correctly rewritten DST. Given that these assumptions are incorrect, some redundancy is introduced to compensate. Two simulation pairs are executed. The first simulation has PV and battery combinations, and 15 optimal solutions. The second simulation pair span PV and battery combinations.

The two comparisons are displayed below.

% Paramaters for Simulation Solution Space

SimParameters = SimulationParameters;

SimParameters.pvStartKw = 100;

SimParameters.pvStopKw = 200;

SimParameters.pvStepKw = 5;

SimParameters.battStartKwh = 1200;

SimParameters.battStopKwh = 1300;

SimParameters.battStepKwh = 5;

SimParameters.llpSearchAcceptance = 0.005;

SimParameters.llpSearchTargets = 0.01:0.005:0.30;

Figure 2:4: Parameters for simulations that produce comparison outputs for simulation pair 1.

Table 5: Results of comparisons in simulation pair 1

|  |  |  |  |
| --- | --- | --- | --- |
| Output A | Output B | n Data Points | Isequal(A,B) |
| SoC | stateOfCharge | 3863160 | True |
| LL | lossOfLoad | 3863160 | True |
| NPC | netPresentCost | 441 | True |
| LCoE | levelizedCostOfEnergy | 441 | True |
| MA\_opt\_norm\_bhut\_jun15\_20\_10(:,1) | lossOfLoadProbabilities | 15 | True |
| MA\_opt\_norm\_bhut\_jun15\_20\_10(:,3:4) | pvKw, battKwh | 15 | True |

% Paramaters for Simulation Solution Space

SimParameters = SimulationParameters;

SimParameters.pvStartKw = 150;

SimParameters.pvStopKw = 170;

SimParameters.pvStepKw = 5;

SimParameters.battStartKwh = 1150;

SimParameters.battStopKwh = 1270;

SimParameters.battStepKwh = 5;

SimParameters.llpSearchAcceptance = 0.005;

SimParameters.llpSearchTargets = 0.10:0.005:0.80;

Figure 2:5: Parameters for simulations that produce comparison outputs for simulation pair 2.

Table 6: Results of comparisons in simulation pair 2

|  |  |  |  |
| --- | --- | --- | --- |
| Input A | Input B | n Data Points | Isequal(A,B) |
| SoC | stateOfCharge | 183960 | True |
| LL | lossOfLoad | 183960 | True |
| NPC | netPresentCost | 625 | True |
| LCoE | levelizedCostOfEnergy | 625 | True |
| MA\_opt\_norm\_bhut\_jun15\_20\_10(:,1) | lossOfLoadProbabilities | 53 | True |
| MA\_opt\_norm\_bhut\_jun15\_20\_10(:,3:4) | pvKw, battKwh | 53 | True |

As seen in Table 5: Results of comparisons in simulation pair 1, and Table 6: Results of comparisons in simulation pair 2, the output matrices are equal. This proves that the rewritten DST preserves the functionality of Logplot.m

#### Computation Speed

The computation speed is a specification in (Mandelli, et al. 2014) and should be maintained in the rewritten DST. An unacceptable change in computation time is when the computation complexity is increased. A small proportional gain is in most non real time application not a problem. The DST is still functional at double computation speed. But a large computation time increase could reduce the users’ perceived quality and satisfaction with the system, and should be avoided.

Matlab has a Profiler timing tool which is used to evaluate the rewritten DST. This tool will list every function call made either explicitly or implicitly by Matlab. The tool will display how much time a function spend waiting for other functions, and how long the program counter works inside the function. The latter is called ‘Self Time’, and will benchmark calculations done within the function without calling other functions. When time is spent waiting for other functions, one should inspect the calls in order to determine if they are necessary. One method of shortening function calls can be to define the functions inline in the script, rather than in a separate file. This was tested with the cycles\_to\_failure function. The improvement was less than 0.1%. The function was kept external to maintain modularity.

The profiler tool output is displayed in Table 7 and Table 8. A large bright blue band will indicate that there might be possible improvements in reducing function calls, and dark blue will indicate self-time.

The rewritten DST will call the modules from a main function. The economic analysis modules is called bugged\_economic\_analysis because a bugg from logplot.m is replicated in order to compare the two programs.

Table 7:The Profiler Tool run on the previous DST. Only the 7 top functions are displayed

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| |  |  |  |  |  | | --- | --- | --- | --- | --- | | Function Name | Calls | Total Time | Self Time\* | Total Time Plot (dark band = self time) | | [logplot](file6.html) | 1 | 4.063 s | 3.986 s |  | | [cycles\_to\_failure](file31.html) | 36500 | 0.046 s | 0.046 s |  | | [finfo](file17.html) | 3 | 0.031 s | 0.015 s |  | | [importdata](file19.html) | 3 | 0.031 s | 0.000 s |  | | [matfinfo>matfinfosub](file25.html) | 3 | 0.016 s | 0.000 s |  | | [mat2str](file26.html) | 3 | 0.016 s | 0.016 s |  | | [matfinfo](file28.html) | 3 | 0.016 s | 0.000 s |  | | […] | […] | […] | […] | […] | | **Self time** is the time spent in a function excluding the time spent in its child functions. Self time also includes overhead resulting from the process of profiling. | | | | | |

Table 8: The Profiler Tool Run on the rewritten DST. Only the 7 top functions are displayed

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| |  |  |  |  |  | | --- | --- | --- | --- | --- | | Function Name | Calls | Total Time | Self Time\* | Total Time Plot (dark band = self time) | | [main](file1.html) | 1 | 5.761 s | 0.000 s |  | | [sapv\_plant\_simulation](file22.html) | 1 | 5.698 s | 5.651 s |  | | [cycles\_to\_failure](file28.html) | 36500 | 0.047 s | 0.047 s |  | | [importdata](file9.html) | 3 | 0.032 s | 0.016 s |  | | [...mulationInputData.SimulationInputData](file21.html) | 1 | 0.032 s | 0.000 s |  | | [bugged\_economic\_analysis](file23.html) | 1 | 0.031 s | 0.031 s |  | | [fileparts](file4.html) | 6 | 0.016 s | 0.016 s |  | | […] | […] | […] | […] | […] |   **Self time** is the time spent in a function excluding the time spent in its child functions. Self time also includes overhead resulting from the process of profiling. |

We can see that the increased computation time is in the Self Time column, the dark blue band, which means that Matlab does not call many additional help functions. The main function in Table 8 has a large bright blue band, because it calls the other module functions. The important take away is that the increased computation time is in ‘Self Time’.

The overhead we experience is not because of calculations, but can be explained as a result of the overhead caused by copying large amounts of variables from the main functions to the modules. Additionally, the rewritten DST has much larger amounts of output data, which will make for memory access and allocation overheads.

The memory access and allocation overhead can be reduced by implementing call-by-reference instead of call-by-value modules. Matlab has handle classes and value classes. In the rewritten DST the value class is currently used. The handle class works like a ‘call to reference’ function in the C language, and will be faster than copying the values. The decision was made to keep the value class implementation. It is likely to be easier to debug, pointer passing tend to produce more cryptic errors, hence complicating development. The pointer functionality can be implemented when the DST is being prepared for shipping.

The overhead in the rewrite is acceptable because of the added modularity and simulation history accessibility in the DST. The only time simulations will be rerun is when the simulation space does not include any desirable solution, whereas logplot.m had to be rerun for a number of reasons such as plotting and investigating a simulation. The user will be able to investigate the simulation space thoroughly and run numerous economic and optimization modules without repeating the simulation step in the rewritten DST.

## Biomass System

A generic system for simulating the use of a biomass system is implemented in the module function pvbiomass\_plant\_simulation. This module is identical to the sapv\_plant\_simulation in the operation of batteries, but also has the contribution from a biomass system for power production. The contribution is added to the needed\_batt\_output variable. This variable is pvPowerAbsorbedKw – load when no biomass generator is running. The system is meant to simulate the use of a generator parallel to the stand-alone PV plant to compensate for low irradiation.

The behavior is not one particular system, it is supposed to be any system choice for generating power with biomass. The system will also be able to simulate whether it is manually operated or fully automated.

### Preemptive Run-mode

The PV usually can have a very high output capacity in terms of kW. To replace this potential capacity can require a very large generator. A large generator is expensive and hence a primary solution rather than a secondary solution. Also, a biomass fueled power generation greater than 30 kW is not typically available off-the-shelf. When running with batteries, we have the opportunity to generate power over time, and hence meeting the demands with a lower output capacity, hence a considerably cheaper solution.

The system assumes that a day with irradiation levels lower than a certain threshold can be predicted with a weather forecast. The power generation can then be started before the battery is unable to meet load demand. For simplicity, we term the low irradiation days as cloudy days and high irradiation days as sunny days.

To simulate a forecasts, the algorithm calculates the pvPowerAbsorbed vector, and finds the peak value. The pvPowerAbsorbedKw values are smoothed because of the nominal irradiation and temperature factors of the PV operation. This calculation is displayed in Figure 2:6 The calculation of the pvPowerAbsorbed vector.

Using the pvPoweAbsorbedKw instead of the irradiation directly, will dampen any irregularly high peaks and give a more intuitive peak value. A threshold is given by the user as a fraction named peakPvPowerAbsorbedTreshold. This threshold will determine if a day is forecast as cloudy or sunny, depending on its relative size compared to the global peak. This comparison is displayed in Figure 2:7 The comparison of peakPvPowerAbsorbedKw values.

At the start of a day, the peak pvPowerAbsorbedKw of the following day is compared to the peak pvPowerAbsorbedKw value of the entire simulation time series. If the peak of the current day is lower than a fraction of the global maximum, the weather is forecast as cloudy, and vice versa.



Figure 2:6 The calculation of the pvPowerAbsorbed vector



Figure 2:7 The comparison of peakPvPowerAbsorbedKw values

When a day is forecast as cloudy, the system will run in preemptive mode until the battery is full, a sunny day is forecast or the biomass/fuel has run out. The entire state machine can be seen in section 2.2.5.

### Startup Delay

The most important generic simulation choice is the startup\_delay parameter, which become relevant during LoL occurrences.

The time needed to start the biomass power generation will vary between solutions. The alternatives range between a very fast response time, for example a gas generator with automated startup at LoL, and a very slow response time, for example a furnace driven steam turbine or an incomplete combustion process, where the response is initiated when an operator discovers the LoL. The very worst case can span hours, as the operator might have to spend time on getting to the plant to operate it, and perhaps additional delays.

The implementation alternative of biomass simulation will involve choosing a generation strategy, such as furnace powered steam generator, and conversion rates of biomass kg to kWh, and respond delays. This implementation would be much like mapping numbers to text, and would do the user a disfavor in hiding the implications of his choices. The preprogrammed time estimates might also not apply because of tweaks or new innovation to the system. A better solution is the one proposed, and complement the solution with information about startup delays and other implications available to the user in online documentation.

### Waiting to Retry

When the biomass system produce power, it will check whether the grid is offline despite the additional contribution. If this is the case, the consumed resources are wasted as the grid is still not functioning. The simulation has a parameter for how long the user prefers to wait if this happens. If the waiting time is zero, the system will keep running, if not the system will start running when the waiting time has passed.

The batteries could be detached from load in this period, and so charged while waiting to retry. This might however cause many extra cycles on the batteries, inducing unpredictable wear on the batteries. A system should not be dimensioned to operate in a potentially destructive way.

### Biomass kg to kWh Conversion

The conversion from biomass kg to kWh will vary between biomass plant solutions, and the conversion rate is therefore left to the user, the biomass supply parameter unit is already in kWh. This is because of the two factors that will be specific for the user’s situation, the plant efficiency and the biomass potential energy density.

The plant efficiency depends on the kind of system implemented, how it’s operated and the system’s quality of design. The biomass potential energy depends on the biomass kind and how the biomass is utilized or refined to power the system. The kind of biomass can also be subject of geographical variations. Because of the amounts of permutations here, it is left to the user to consult the biomass system manufacturer, people with experience from a similar plant and with the same materials and potentially make some assumptions in order to find the supply in kWh.

An implementation that does the conversion job for the user carries a large risk of making imprecise or outdated assumptions, which can be cascaded and therefore amplified, when combined with other imprecisions. The conversion is simple math with many parameters, which will be simple for anyone with the resources to implement a power plant. This way the user maintains control of the assumptions. The monitoring of produced kW should be simpler than weighing, as biomass also change weight and potential energy as the moisture changes.

### The Biomass-System State Machine

The implementation of the system biomass simulation was done with a state machine. A state machine has the benefit of only allowing the system to be in one state at any time. This will simplify check of conditions as a state has a limited number of allowed transitions. The state machine implementation will make the code more readable and the program flow comprehensive. It also provides a sketch of the desired functionality. This is useful when implementing as a graphical specification.

The transition diagram can be seen in Figure 2:8. The diagram illustrates the transitions between states without any implementation details.

\\webedit.ntnu.no\gardhi\dstReferenceManual\biomassSystemStateMachine.png

Figure 2:8 Biomass System State-Machine Transition Diagram

### pvbiomass\_plant\_simulation.m

The system state is kept in the variable biomassSystemState. This can be in the following states ‘Idle’, ’Starting Up’, ’Running, ’Running Preemptively’, ‘Waiting to Retry’ and ‘Waiting for Biomass’. The states can perform two actions, they handle transitions to new states, and they set the runBiomassGeneratorHours variable. This variable decides how long the biomass generator should run the current hour. The generator effect code block is executed after the state machine. If the runBiomassGenerator is positive, for example 0.5, it means that the generator should run for 30 minutes. When power contribution of running time is processed, the runBiomassGenerator variable is set back to zero for the next iteration.

When the biomass system generates power, the contribution is subtracted from the neededBattOutputKw variable, the same way power contribution from the PV is subtracted from the load (with losses) to calculate the neededBattOutputKw variable. The biomass contribution is not subject to inverter loss, as mechanical generators output AC power.

The system can be in two states during one hour iteration only if the system changes to the waiting state ‘Starting Up’. This is necessary as waiting time can be less than one hour, and require the system to respond before iterating to the next hour. When the timer is less than 1 hour in a waiting state, the remaining time is calculated. The generator output and biomass consumption is scaled to fit the amount of time of running, found in the variable runBiomassGeneratorHours. The neededBattOutputKw is also scaled accordingly, when comparing to see whether the output is insufficient.

#### Runtime

The code displayed in section 2.2.6.4 Biomass System Source-Code, is executed every hourly iteration of the simulations. There are no further loops, computational complexity is therefore not increased and runtimes will stay within a predictable scale. The overhead of the state machine is a constant that increase the run-time about 10 times. This is justified as the user is expected to narrow the number of simulations, before speculating in biomass implementations. The extra run-time is strictly self-time as discussed in section 2.1.4.2 Computation Speed, meaning that there are no external functions slowing down runtime.

#### Additional Outputs

Biomass system output kW for each hour is added to the SimulationOutputs class. The BiomassOccurrences struct is also passed to the output class, this struct counts the occurrences in the state machine in terms of hours and events, to enable performance monitoring.

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| \\webedit.ntnu.no\gardhi\dstReferenceManual\StateMachineFlowchart.png  Figure 2:9 The Biomass System Implementation Flow-Chart |

#### Biomass System Test Results

Goes here

#### Biomass System Source-Code

% biomass system state machine initialization

runBiomassGeneratorHours = 0;

biomassSystemState = 'IDLE';

previousState = 'RUNNING';

% remove rest of biomass from previous simulation

availableBiomassKw = BiomParam.biomassDeliveredKw;

[…]

% delivering biomass

if mod(t, BiomParam.biomassDeliveryIntervalDays\*24) == 0

availableBiomassKw = availableBiomassKw ...

+ BiomParam.biomassDeliveredKw;

end

% A new day starts and the system is preemptive

if mod(t,24) == 0 && BiomParam.isPreemptive

% the predicted weather is cloudy

if strcmp(weatherPredictions{t/24 + 1}, 'cloudy')

isSunny = false;

if strcmp(biomassSystemState, 'WAITING TO RETRY')

previousState = 'RUNNING PREEMPTIVELY';

else

biomassSystemState = 'RUNNING PREEMPTIVELY';

end

% the predicted weather is sunny

else

isSunny = true;

end

end

% STATE MACHINE -----------------------------------------------

% RUNNING PREEMPTIVELY-----------------------------------------

if strcmp(biomassSystemState, 'RUNNING PREEMPTIVELY')

% the system should stop running preemptively because of

% sunny weather or full battery

if isSunny||(stateOfCharge(t,iPv,jBatt) == 1)

biomassSystemState = 'IDLE';

% we stay in preemptive mode

else

runBiomassGeneratorHours = 1;

end

% RUNNING------------------------------------------------------

elseif strcmp(biomassSystemState, 'RUNNING')

% PV can handle the supply alone

if neededBattOutputKw(t,iPv, jBatt) < 0 ...

|| stateOfCharge(t, iPv, jBatt) == 1

biomassSystemState = 'IDLE';

% we stay in running mode

else

runBiomassGeneratorHours = 1;

end

% IDLE---------------------------------------------------------

elseif strcmp(biomassSystemState, 'IDLE')

% The battery is at minimum and power is insufficient

if (stateOfCharge(t, iPv, jBatt) == BattParam.minStateOfCharge)...

&& (neededBattOutputKw(t,iPv, jBatt) > 0);

biomassSystemState = 'STARTING UP';

startupDelayTimer = t;

end

% INSUFFICIENT BIOMASS-----------------------------------------

elseif strcmp(biomassSystemState, 'INSUFFICIENT BIOMASS')

% Count hours spent waiting for biomass

BiomOccurrences.waitingForBiomassTime(iPv,jBatt) ...

= BiomOccurrences.waitingForBiomassTime(iPv,jBatt)...

+ 1;

% more biomass is available

if availableBiomassKw > BiomParam.generatorOutputKw

% prepare for normal operation

biomassSystemState = 'IDLE';

end

end

% STARTING UP--------------------------------------------------

if strcmp(biomassSystemState, 'STARTING UP')

% The time left

residualTime = BiomParam.startupDelayHours...

- (t - startupDelayTimer);

% The generator is not needed

if neededBattOutputKw(t,iPv, jBatt) < 0

biomassSystemState = 'IDLE';

% The timer is done

elseif residualTime <= 1

% run the generator

runBiomassGeneratorHours = residualTime;

biomassSystemState = 'RUNNING';

end

% WAITING TO RETRY---------------------------------------------

elseif strcmp(biomassSystemState, 'WAITING TO RETRY')

% The time left

residualTime = BiomParam.retryDelayHours ...

- (t - waitToRetryTimer);

% Account for time spent waiting to retry

BiomOccurrences.waitingToRetryTime ...

= BiomOccurrences.waitingToRetryTime + residualTime;

% The timer is done

if residualTime <= 1

% The timer finish this hour

if residualTime >= 0

% run the generator

runBiomassGeneratorHours = residualTime;

% The timer finished last hour

elseif residualTime < 0

runBiomassGeneratorHours = 1;

end

% return to previous state

biomassSystemState = previousState;

end

end

% The biomass generator should run for runBiomassGeneratorHours

if runBiomassGeneratorHours

generatorOutputKw = 1 - runBiomassGeneratorHours...

\* BiomParam.generatorOutputKw;

% There is sufficient biomass

if availableBiomassKw > generatorOutputKw

% The needed output is larger than generator kw size

if (neededBattOutputKw(t,iPv, jBatt)...

\* runBiomassGeneratorHours) > generatorOutputKw

biomassSystemState = 'WAITING TO RETRY';

waitToRetryTimer = t;

previousState = biomassSystemState;

BiomOccurrences.waitingToRetry(iPv,jBatt)...

= BiomOccurrences.waitingToRetry(iPv,jBatt) + 1;

% The generator will still run the given time

% before the insufficient output is discovered.

end

neededBattOutputKw(t,iPv, jBatt) ...

= neededBattOutputKw(t,iPv, jBatt)...

- generatorOutputKw;

biomassGeneratorOutputKw(t,iPv,jBatt) ...

= generatorOutputKw;

availableBiomassKw = availableBiomassKw...

- generatorOutputKw;

else

biomassSystemState = 'INSUFFICIENT BIOMASS';

end

% will only run what the state machine outputs.

runBiomassGeneratorHours = 0;

end

### economic\_analysis\_biomass.m

There were some additions to the original economic analysis to include the biomass system. When calculating a system with biomass, the economic\_analysis\_biomass.m module can be called. The additions to the outputs in EconomicAnalysisOutputs are the variables bioSysNetPresentCost, biomassPresentCost and bioSysLevelizedCostOfEnergy. These are the NPC of the entire biomass system installation, the money spent on biomass in present cost and the present cost of each kW produced by the system. It is assumed that the lifetime of a biomass system is approximately the same as the PV-plant and that there will be no significant salvage when the period has ended.

The LCoE is calculated by splitting the NPC into equal annual payments, including interests during the down-payment period. This annual payment is divided by the kWh successfully delivered to the load during simulation, which gives us the present cost of each kW.

The additions to the economic analysis can be seen in Figure 2:10.



Figure 2:10 Additions to the Economic Analysis module

### The Results of running the Biomass System

The system was tested without PV and in parallel to the PV. The economic analysis shows that the implementation of biomass system can improve the performance and economic outlook of the plant, this is shown in the use case presented in section 3.1 A Brief Use-Case for the DST.

The system was tested as a stand-alone biomass microgrid and in parallel with PV power generation.

#### Running without PV

When running with only biomass generators, the parameters of the system was input so that the system would be large enough to support the entire load alone. The result was a functioning supply which had a small LLP for every non-preemptive startup of the generator.

In any real life use case, the generator would be turned on at regular intervals every day and these LLP’s would not exist. This module is not made for stand-alone biomass generation and hence any modifications to optimize this functionality is neglected.

The result of one simulation can be seen below, there are examples of both preemptive and non-preemptive behavior in the system.

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| Figure 2:11 State of Charge with only biomass generator and Preemptive-mode active |

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| Figure 2:12 Power balance with only biomass generator. non-preempitve bahavior to the left, preemptive bahavior to the right |

#### Running with PV

## Graphical User Interface

For development purposes, a graphical user interface (GUI) is implemented as a part of the DST. The GUI will help developers to understand the needs of the user and works as a prototype for the finished DST. The user interface programing in Matlab involves initiating different uicontrols. These are objects that are constructed by setting their type, appearance, position and defining their call-function.

The call-function is called every time the object is interacted with. In figure Figure 2:11 and Figure 2:12 an example of a uicontrol initiation is displayed, and its call-function.



Figure 2:13 The uicontrol initiation for the 'Run Optimal Solutions' button



Figure 2:14 The call-function when pressing the 'Run Optimal Solutions' button

### dst\_platform.m

The dst\_platform GUI is meant as the start platform for the user. The main function of the GUI is to initiate the parameter classes, and pass these classes to different modules depending on the GUI run-settings. This tool vastly simplifies testing of new functionality. One can run a new module by changing which function to be called at button press, make a new run button, or simply use the tool to initiate the classes and pass the parameters manually.

The GUI can save presets, meaning that any combination of inputs and settings to the dst\_platform can be saved and will load when it is chosen from the dropdown menu. This will allow the user to inspect the differences between different input parameters, and retrace old settings at a later time. Saving is done by entering a name for the current preset and pressing ‘Save’, this will overwrite any preset with the same name. Pressing ‘Delete’ will delete the currently chosen preset in the dropdown menu.

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| \\webedit.ntnu.no\gardhi\dstReferenceManual\dst_gui.png  Figure 2:15: the DST Platform GUI |

The dst\_platform also has a plotting functionality to get a comprehensive overview of the simulation output space. This plot will appear when pressing the ‘Simulation Overview’ button. A detailed description can be found in section 2.3.3.1 Simulations Overview.

The ‘Help’ button will open a browser window with the online documentation of the DST, this is described briefly in section 2.4 Documentation.

The ‘Input Data Files’ panel is where the filename of the different input files are passed from. The ‘Data Set’ field is the folder with the different files belonging to the same data-set.

The ‘Run Solution Explorer’ button will open the Solution Explorer GUI which is designed to compare and evaluate solutions found by the optimum search. The Solution Explorer is described in detail in section 2.3.2 solution\_explorer.m.

#### Running-Modes Available to the DST platform

Under the ‘Run Calculations’ header, there is a checkbox for ‘Generation Strategy – Biomass’. This run-mode will be described in section 2.2 Biomass System. When checked, the system will simulate with a generic operation of a biomass system, parallel with the PV panel.

The ‘Optimal Solution Output’ radio-button choices below the biomass checkbox decide which optimization module that should run. The ‘LLP Constrained’ optimums is the original optimization from logplot.m, this is now the llp\_constrained\_optimums function. This module will iterate through a set of LLP values. If one or more matches of LLP are found in the simulation output space (with a given acceptance), the simulation with the lowest NPC is chosen as the optimal solution.

The ‘NPC Constrained’ optimum search works the same way, the difference is that instead of searching a range of LLP, it searches a range of NPC, and picks the smallest LLP as the optimal solution when a match is found. The module is implemented in a function called npc\_constrained\_optimums.

The ‘LCoE Constrained’ optimum search will call the lcoe\_optimums module. This function simply chose the lowest LCoE in the simulation output space. It will also generate a warning if the lowest LCoE is found at a boundary, indicating that there might still be lower LCoE values in solutions if the simulation space is expanded further.

A detailed explanation of all the functions and modules, are available in the online documentation at <http://folk.ntnu.no/gardhi/dstReferenceManual/referenceManual.html>. The functions are not explained here as they are only utilized by the DST platform as external modules.

### solution\_explorer.m

The solution explorer is implemented to assist the user in understanding the results from the DST. The solution explorer allows the user to choose different solutions and compare them to other solutions. There are a number of outputs that are seen as essential to understand the implications of a choice. These belong to ‘General Info’, ‘Averages’, ‘Worst Case’ and ‘Biomass’.

The Solution Explorer is a way of analyzing the simulations chosen from the optimal search modules. These are stored in the Optimal Solutions class. The tool lists all the solutions stored in the variable ‘OptSol’ in the workspace, as seen beneath the text ‘Pick a Solution to Examine’ in Figure 2:15. Here are some key values to characterize the overall functionality of the simulation, these are NPC, LCoE and LLP. Once a solution is highlighted, the different buttons will produce outputs for examining the current solution.

Each solution has indexes in the different output matrices. These are normally referred to as iPv and jBatt in the code context, in the output windows this translates to ‘PV iteration’ and ‘Battery iteration’.

The radio toggle buttons under the Data Analysis Output windows decide which window the output should appear on. If the ‘Output In New Window’ option is chosen, outputs will appear in a new floating windows. This choice will allow for more than two windows for comparison. This is displayed in figure Figure 2:14 A floating Worst-Case Ouput Window. Plots will always appear in new floating windows (plot default behavior).

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| Figure 2:16 A floating Worst-Case Ouput Window |

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| \\webedit.ntnu.no\gardhi\dstReferenceManual\solution_explorer.png  Figure 2:17 The Solution Explorer |

#### Available Outputs to the Solution Explorer

The different buttons will output different kinds of information. A LoL value alone is not enough to understand how a system operates. For example, these outputs gives the user an idea of whether the LoL stems from some incidences of lost load, or from a regular daily small LoL. The latter, frequent lost load occurrences, is a worse alternative. A few occurrences of high magnitude of lost load is less critical.

‘General Info’ serves as an overview of recognizable characteristics for the user. The output includes which simulation the solution is pointing to in terms of kW/kWh and indexes, several totals and counters. The counters are for battery replacements during plant lifetime, which are very expensive and also connected to some risk, and occurrences of lost load.

‘Averages’ are for understanding of the general performance of the system. As mentioned earlier we want to know if the system is regularly offline or if there has been some large occurrences, this is visible in terms of time when comparing ‘Average Downtime Length’ and ‘Daily Average Downtime’, and in terms of kW when comparing ‘Average Lost Load During Downtime’ to ‘Daily Average Lost Load’. The outputs from ‘Worst-Case’ are also relevant here.

‘Worst-Case’ will tell you about the different worst-case scenarios for our system. Here we have specific intervals within the time series, and so the time when worst cases occur is also displayed. This way the user knows whether the worst cases are connected. The worst cases also gives an understanding of potential difficulties of running the system. By comparing worst case to averages, the user will understand better what kind of conditions that might occur, and how probable they are. If the worst case is close to the average, the user might have to consider expanding margins in case these conditions might occur more frequently.

‘Biomass-System’ delivers an overview picture of how the biomass system worked and the costs of running and implementing it. The LCoE of the biomass system will enable a comparison of the final cost per kWh of the system. The running times and transitions communicates how well the system is scaled, and how it works compared to its purpose. For example, much time spent in ‘Waiting To Retry’ indicates that the generators kW output is too small to handle the LoL magnitudes.

The unused generator output indicates the extent of failed attempts of running the generator. These attempts fail when the output kW is too small to cover the load, and the generator is shut down until the waitToRetryDelay has finished.

### Plots

Plots are important in the DST. Users can visualize the hourly levels in order to understand how the system work, but also when and how much the micro grid fail. The previous DST would not allow any single function to run without running entire simulations. In the case of plotting, one would have to simulate the system in order to find what solution (combination of PV and battery) one wished to examine, then one would have to hard-code the DST to plot this solution as it was iterated over. This continuous hard coding and redundant computation was vastly time consuming. The rewritten DST has one function for each plot.

#### Simulations Overview

It is vital to understand the simulation space when trying new parameters to the system, or when searching for a feasible solution. The simulations Overview plot is implemented in order to see the results in a larger context, to understand how solutions appear in the simulation space.

The plot is immediately useful when limiting the simulation space and when changing solution resolution, as the first step of using the tool and changing the SimulationsParameters input.

The plots have the same layout as the matrices of which they represent. The matrices plotted in Figure 2:16 are LLP, LCoE, number of batteries employed and NPC. The units in these are assumed understood by the user, the units of currency depend on what currency the user choose as parameter standard.

The tool plotter (the beige square in the upper left figure) can pick single solutions to retrieve iPv, jBatt, the indices of the solution, and the corresponding z-value. The left hand bar display the color legend in the figures. The 3D pan can be used if desired to see depths in the plots, these are by default displayed from above to avoid ambiguities.

The simulation overview will allow the user to spot trends in the solution space. This is important when navigating design choices. There is however a risk that the decisions are based on uncertain results. There is a varying degree of certainty associated with a simulation space, depending on the precision of the parameters. A decisions based on a higher precision than what is achieved, carry the risk of being a poor choice. To make finely tuned decisions the user will have to know the uncertainties of the parameters and how they are used together.

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| Figure 2:18 The simulation Overview Plot of SAPV simulations |



Figure 2:19 The Simulation Overview Plot module source-code

#### State of Charge

The SoC plot is inherited from logplot.m, it is now a single module with some minor layout changes. It will access any simulation given by its indices iPv and jBatt and plot the full time series of the simulation. This is a very useful plot as it makes a comprehensive interpretation of the lossOfLoad, batteryOutputKw and pvAbsourbedUnusedKw vectors, and their relationship. All kW values are normalized with respect to the battery capacity.

The green plot line is power from the PV that neither serves load nor charges batteries because of fully charged batteries, this has the offset of 1. The red plot line indicate loss of load in kW, the values are negated and with offset value equal to minimum SoC. This is nonzero when there insufficient output to serve the load from neither PV nor battery, or if discharge demands are too large.

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| Figure 2:20: A Full Year of the State Of Charge Plot |

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| Figure 2:21: 10 Days Range of the State of Charge Full-Year Plot |

When seeing the full year span of the SoC plot, you can see the frequency and depth of the loss of load in the red lines. This gives a good understanding of how the system performs, it would however be useful to see how this affects the average day.

When plotting the average day of SoC it lose most of the original expressive power. Because the plot lines are normalized and rely on the continuity of the curve to communicate the battery dynamics, when the hourly average of 24 hours is plotted, the continuity disappear and the magnitudes start making less sense, this is seen in Figure 2:20 An Average-Day State Of Charge Plot.

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| Figure 2:22 An Average-Day State Of Charge Plot |

#### Power Balance

The initial idea of the power balance plot was to enable comparison between irradiation input and load profile. An average day plot to indicate how each hour of a day normally operates is desired, and require a plot that is not normalized. This will help to understand when the system normally fails, and how much the system deviates from its desired operation.

Logplot.m contains an implementation of this, but the plot had several errors. The legend does not describe the plotted values correctly. The variable names in logplot.m and a lack of testing, complicated by the lack of naming convention and modularity respectfully, are probably to blame. These things are improved in the rewritten DST.

The yellow plot line seen in Figure 2:21 is the value from the variable named P\_pv in logplot.m. The legend says ‘Energy from PV’, but in reality this is the absorbed power, not the utilized power. Consequently, some of this power never serves the load, nor charges the batteries.

The brown plot line is the values from the variable bat\_balance\_pos in logplot.m. The legend says ‘Energy flow from battery’, but in reality, this is the needed battery output, demanded by the load. The plot will therefore express a perfectly functioning system every time, the ‘needed power’ is described wrongly as ‘supplied power’.

The difference between the blue load and the brown plot line in the part where only battery supplies the load, is only from efficiency losses which proportionally increase the needed battery input.



Figure 2:23: The power balance in logplot.m.

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| Figure 2:24: The average-day version of the Power Balance plot from logplot.m |

The code for plotting the power balance in logplot.m is displayed in Figure 2:24 and Figure 2:23. The latter is the same snippet of code with the naming convention from the rewritten DST. It is now easy to see that the legend and names have conflicting meanings. It is likely that these errors would not have been made with the new naming convention.

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Figure 2:25: The code for plotting of the Power Balance in logplot.m

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Figure 2:26: The same code as in Figure 2:23, with the new naming convention

The Power Balance plot is rewritten as a module with the intended functionality from logplot.m. Like the other plots, the module is implemented as a function. The only input that has to change when calling the plotting functions is the indexes of the desired simulation in the simulation space, iPv and jBatt. This makes it easy to call the function from the current workspace, and to plot simulations without much effort despite lacking a UI, like the dst\_platform.

There is one function for plotting the average day, and one for plotting the full year of power balance. These are identical except for the part of calculating daily averages. The choice of not locating this functionality within one function, and not determining the average-day mode with a passed input is to reduce the knowledge needed to utilize the function. This is a key principle of modularity.

The utility of the new Power Balance plot is to compare the different power outputs in scale with each other. When the system supplies the load perfectly, the system is in an equilibrium that is expressed graphically. This is done by plotting all the power to the load after losses. These values are labeled ‘net’ in the plot code to express that every kW goes to the load.

The batteryNetOutput is the battery discharge that reach the load without losses. The values of battOutputKw are positive when the battery discharges. The discharged variable is a vector with the positive values of battOutputKw that is returned by the subplus function. This vector is scaled down with discharging efficiency and the inverter efficiency, this gives us the battNetLoadSupply vector.

The pvNetLoadSupply is the power that is directly supplied to the load from the PV. These values are not output as a vector from the simulations module explicitly. Too many output vectors will take time to compute and will increase the memory-use of the program, this is not justified by a single plotting functionality.

The pvNetLoadSupply is found in two steps. Either the neededBatteryOutput is negative, meaning that the battery is charging. In this case the power from the PV is greater than the load, hence every value in the load variable can account for supplied PV power. In the second case neededBattOutputKw is positive. This means that all the pvPowerAbsorbed goes to serve the load directly and is therefore equal to pvNetLoadSupply.

irradiationUtilized is the pvPowerAbsorbed – pvPowerAbsorbedUnused. The latter accounts for power wasted when the batteries are fully charged, or when the batteries maximum charging rate is exceeded. The utilized irradiation goes to serve the load without any losses, or to the battery with losses. The latter makes the irradiation utilized slightly off-scale from the load, meaning that the summed integral of irradiationUtilized subtracted with the summed integral of netLoadSupply is nonzero. This slight offset does however not disrupt the comparison of the three curves.

The code for the plot\_average\_power\_balance function is displayed in Figure 2:25. The calculation of averages is supported by the generic help-function get\_average\_day. The help function is used different places in the DST and helps reducing development effort and increase readability.

get\_average\_day finds the average value of all 24 hour segments a vector. The input vector must have hour resolution. The function is displayed in Figure 2:26.



Figure 2:27 The plot\_average\_power\_balance function.



Figure 2:28 The get\_average\_day help-function

Instead of plotting pvNetLoadSupply and battNetLoadSupply separately, they are summed together. This will result in a perfect tracking of the load curve when the system functions perfectly, and a deviation from the load curve during loss of load. When this occurs, the blue netLoadSupply plot-line will sink and reveal the red load line. This will make it clear when the power fails, this can be seen in Figure 2:27.

The origin of power can also be followed in the plots. When irradiationUtilized is non-zero, the PV power will always first cover the load, if the irraditationUtilized is zero, the battery will support the load alone. Hence the integral of the difference between netLoadSupply and irradiationUtilized is the battery output, without the loss while charging/discharging and in the inverter. In the case of 90% efficiency in each transition, the integral difference is 72.9% of the actual battery output.

The integral of irradiationUtilized and netLoadSupply will not sum to zero, but one can still see the proportions of energy input and load demand. It will help the user understand the magnitude of the lost load in terms of irradiation and battery dynamics.

The new colors aim to appeal to intuition. If the system is functioning well, the red line is hidden by the blue line. The irradiationUtilized is yellow so that the user understand its role, without necessarily reading the legend.

The resulting plots can be seen in Figure 2:27 and Figure 2:28. The functions are easily maintained and modified because of modularity.

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| Figure 2:29: The new Power Balance plot, 4 days of the full-year plot. | |
| Figure 2:30: The average-day Power Balance plot. |

## Documentation

To maintain a continuous documentation that is platform-independent, easily maintainable and easily accessible. The new DST has online documentation written in HTML. The code is in rudimentary HTML which can be modified and understood by anyone. HTML can additionally be written by practically any device. This enables continuous development of the documentation as the tool grows and is modified, it will also allow documentation to be read from a phone or any platform with an internet browser installed.

The idea is to have a minimalistic documentation that is easily navigated by a browsers search-functionality. If the user finds a function, parameter or variable that needs explanation, the name of the component can be input with ctrl+f and the explanation will appear without having to click any hyperlinks as everything is in one page. Additionally there is a table of contents and a link to the top on the page, this can be handy if one is investigating several objects. See Figure 2:29.

The documentation is organized in 6 main parts. ‘Notes to the User’ is reserved for the most vital information needed to work with the DST. ‘Modules’ explain the main modules of the DST, their inputs, outputs and functionality. ‘Classes and Properties’ explain the different classes that is used to pass variables between functions. These contain explanations for every large-scope variable in the DST. ‘Plots’ will explain how to use and interpret the plot functions, and lastly the ‘Help Functions’ is a summary of the globally accessible functions, used different places in the DST.

The documentation is several pages long and can be found at <http://folk.ntnu.no/gardhi/dstReferenceManual/referenceManual.html> or <http://gardhi.github.io/dstReference/referenceManual.html>. When someone wants to inherit this code it is sufficient to download the script from the webpage. The Git-hub repository will also be open for collaborators.

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| Figure 2:31 The DST Online Reference Manual |

# : Summary and Recommendations for Further Work

## A Brief Use-Case for the DST

In this chapter the use case of the DST will be presented. The GUI is initialized by running dst\_platform.m this can be done by writing dst\_platform in the matlab console

### Research and Parameter Input

Arguably the most difficult part of using the DST. The first thing one need to consider is what kind of battery type one wish to purchase. When this is established, the cycles\_to\_failure function needs to be updated. The function is a fitting how many cycles the battery can handle at a certain level of discharge, before breaking down. This will be supplied by the battery manufacturer. The user must make sure that all currencies are the same.

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| \\webedit.ntnu.no\gardhi\dstReferenceManual\cyclesLocation.png |

When this is done, the parameters need to be updated. This mainly involves finding products, gathering the technical specifications from manufacturer or distributor and input this to the dst\_platform GUI. Before a biomass system is included it is wise to refine the SAPV simulation space first as the computational time is considerably (10 times) faster.

If some questions arise during input, the large ‘Help’ button opens a browser window with the online reference manual documentation. Here are sources of the more complex inputs, and the user can choose to trust or inspect closer.

When all the parameters are input, the files of input data: irradiance, ambient temperature and load profile filenames must be saved in the ‘database’ in a new folder named after the data set, in this case we use data from the Bhutan project. If the vector sizes are different, the program will warn you about this as the class constructors forbid it.

Now the preset of all the data input can be saved as a .mat file, here we have named the preset ‘NewSystRefinement1’. This is to keep track of everything done so that solutions can be retraced if inspection becomes necessary.

### Simulation-Space Refinement

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| Figure 3:1 The Starting Point of Simulation-Space Refinement |

Now the simulation-space must be refined, this means that the simulations that you don’t wish to consider should be excluded from the simulation-space. This will allow for a more detailed solution space and much faster computation time. Guess the PV and battery size starting points if you don’t know what order of sizes are appropriate.

Pay attention to the iteration-counter in the upper right corner, each of these simulation needs loop 8760 times for each year in the input vector.

The ‘Run All Modules’ button can be used, or the ‘Run Plant Simulation’ followed by the ‘Run Economic Analysis’ buttons which will be queued for execution when the simulation step is finished. The simulation overview button is pressed to explore the simulation-space.

When the ‘Simulations Overview’ plot appears, you need to determine what qualities that lie within which ranges in the plot. If you happen to be color blind, the ‘Rotate 3D’ button in the Matlab figure window will allow you to see a contour plot instead of the color scale bar, the Data Cursor will then tell you what values different depths represent.

In figure Figure 3:2 the user has decided that a LLP of 5% is the maximum accepted LLP, the choice is reflected in the other windows as they represent the same iterations of PV and battery. The new PV start-value is then precisely pvStartOld + iPv\*pvStepOld and the same with battery battStartOld + jBatt\*battStepOld. It is expected that the user will make a rough estimation of the new range or perform this simple calculation. In this case the new simulation range can for example be:

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| --- | --- |
| **pvStartKw** | 400 |
| **pvStopKw** | 500 |
| **pvStepKw** | 5 |
| **battStartKwh** | 1350 |
| **battStopKwh** | 1600 |
| **battStepKwh** | 5 |

The step size has been reduced and the difference between each solution is then smaller. If the resolution is satisfactory and the NPCs acceptable, we can start to explore solutions.

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| Figure 3:2 Refining the Simulation-Space |

### Solution Exploration

We can now take a better look at the solutions provided within the simulation-space displayed in Figure 3:3. Notice the sharp jump in values as the number of battery replacement increase, the user will have to consider the quality of his inputs to the DST if dimensioning close to these jumps. It is probably wise to have some distance if the economical margins are tight..

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Figure 3:3 Refined Simulation-Space

To open the solution\_explorer, the ‘Solution Explorer’ button is pressed, or solution\_explorer typed in the Matlab console. The user can now investigate the qualities of the optimal solutions. By default the ‘LLP Constrained’ optimums are found, but this can be changed to NPC or LCOE minimum if desired, after changing the optimum search method only the ‘Find Optimal Solutions’ button should be pressed so that the simulation steps are not unnecessarily repeated.

The ‘LLP Optimum Search Constraints’ displayed in the blue square that is step 5 in Figure 3:1 are set to the values in Table 9, before opening the Solution Explorer

Table 9 LLP Optimum Search Constraints

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| --- | --- |
| **LLP Search Acceptance** | 0.1 |
| **LLP Start** | 0 |
| **LLP Stop** | 5 |
| **LLP Step** | 0.5 |

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| Figure 3:4 Choosing solutions in the Solution Explorer |

The following step can be difficult because the user must decide what measures of quality should be more prioritized. When a solution is chosen in the ‘Pick a Solution to Examine’ window, outputs and plots can be produced quickly by pressing the different buttons. If the user wants to compare more than two windows, the ‘Output in New Window’ radio-button can be chosen.

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| Figure 3:5 Comparison of different solutions after the running the SAPV system |

### Problem Solving

How should the system solve its’ short comings? The options available here are either that the user decides that some characteristics are more desired than others after inspecting the solutions, that the grid budget has to cover a smaller amount of load, or to explore a biomass system parallel implementation.

The biomass system takes longer time to compute, depending on the performance of the system one might want to narrow down the simulation space when doing this. The solutions that were produced for the SAPV system can be saved in separate windows to compare the performance and cost of the two technologies.

### Decide on a System Purchase

The user can run a biomass simulation with similar ranges as for the previous simulation-space. This round the user might want to see the results with an NPC close to the one found with the SAPV system. The ‘Biomass’ check box is checked under ‘Generation Strategies’ and the ‘NPC Constrained’ radio-button is toggled under ‘Optimal Solution Output’.

Utilization of the biomass generation strategy and comparison can be seen in the figures on the next page. This example incorporates a very cheap biomass system as operations cost are very low and biomass is free. The result is that the LLP, LCoE are lower. Following from the LLP the performance data is improved substantially for a very small price compared to the same performance increase in SAPV. This is due to the flexibility of the generator.

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| Figure 3:6 The Operation of the Biomass Generator in the Power Balance plot |

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| Figure 3:7 Including the Biomass Generation Strategy |

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| Figure 3:8 Several Windows from the SAPV simulation and Biomass simulation compared |

## Summary and Conclusions

Through renaming every variable to optimize the readability of the DST, the design flaws and inner working of the tool became apparent. It was discovered that certain parts of the hard coded and hard-to-find parameters were responsible for….

## Discussion

### Biomass Power Generation

Usefulness

Inconsistency

### Applicability of DST

Simulation space battery replacement steps

## Recommendation for Further Work

### Finding Borders Analytically

The DST relies initially on producing a very large solution space. The user will usually have to create the simulation space more than once, to pinpoint the desired resolution for analysis. A user might not familiar with the economic proportions of the PV and battery sizes necessary for the load in question. If this is the case, the user has to start with a wide solution space and then iterate to the desired scope and resolution for analysis.

The outputs used from the simulation module for the economic analysis is the yearsBattOperational value, stating how long a battery is functional, and the lossOfLoadTot for the time series. The years a battery is operational depends on the wear and tear of the system. This value does have a worst case outcome, if every cycle is a full discharge to the minStateOfCharge level. The following analytical expression will calculate this worst case life span.

YO stands for years operational, the years a battery is operational before being replaced. Using this in the economic analysis we achieve a degree of freedom to find sizes for PV and battery expressed by B kWh and PV kW in the following equation:

OeMeR is the net present cost of operation, maintenance and replacement of batteries. B cost/kWh is the cost of batteries per kWh. I cost is the inverter cost. PL is the plant lifetime, YR is the years remaining of battery life after plant lifetime has expired, and OeM cost/kW is the yearly operation and maintenance cost per kW of PV capacity.

If we assume that IC and OeMeR are known, the equations have 2 unknown variables and the system has a solution. A problem is that the ratio between OeMeR and IC will affect the solution in different ways. This means that the user must know what ratio between the two is to be expected. This is problematic. If we have that in systems in general, we can exploit that:

This will enable the user to know only the NPC to get a minimum performance size for this budget. A histogram from the test data shows that the ratio is varying more than 10% as seen in Figure 3:5. This might be too much to make any useful estimates.

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Figure 3:9 Distribution of IC/OeMeR ratios

#### Suggestion for Future Work

A possible connection between the IC/OeMeR ratios and LLP is displayed in Figure 3:6. A general analytical expression may be found from several test-data sets empirically. The results would be useful if precision is consistently higher than 10% deviations. Using these results, a component minimum size can be returned to the user without any exploration of the simulation space.

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Figure 3:10 Dependency between LLP and IC/OeMeR ratio

list of figures

# : Appendences

1. The DST Source-Code

The DST source-code is found online on <https://github.com/gardhi/DST>. To inspect the code one only need to have a browser and internet, to run and test the code the code needs to be downloaded through Git.

Git is a version control program that allows for agile collaboration on projects, the use of Git is established throughout the programming world and widely used by the majority of professionals.

**Instructions on Downloading and testing the DST**

1. Install a Git client from anywhere.  
   For a desktop easy-to-use interface download github here:  
   <https://desktop.github.com/>
2. Open the Git Shell.  
   If you are using windows, press the windows-button and write: Git Shell
3. Clone the repository.  
   While using the git shell, navigate to the folder where you want the project to be placed. Cloning basically means downloading, this is done in the current folder by writing: git clone “http://www.github.com/gardhi/DST”  
   It should look similar to this:

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1. Run the code.  
   You now have the entire project in the destination folder, open it in Matlab and include the folder DST to path and all subfolders.

**To run the DST, simply write** “dst\_platform” **in the Matlab console window once the folders are on the Matlab path.**

1. Contribute!  
   To work on the project, make a branch either in GitHub desktop or in the shell.  
   When your feature is finished it can be added to the project by a merging your branch with the master branch, and then pushing to the origin, or by a practice determined by project administrator. In this case a pull request is required, documentation is found online.
2. The Reference Manual Source-Code

The reference manual has an online repository on github just like the DST. The repository address is <https://github.com/gardhi/dstReference> and can be cloned just like described in Appendix A.

For a faster way to inspect the source code one can visit the webpage of my NTNU server. <http://gardhi.github.io/dstReference/referenceManual.html> and right-click, Save As and choose format to be webpage complete.

The ownership of repositories will be transmitted to any successors of the project.

1. The Rainflow Counting Algorithm

As there were some doubts about this implementation this study of the Rainflow Counting algorithm used in the code was conducted to verify it’s correctness.

It is highly important to consider the calculations of the battery replacement interval. Replacing batteries are costly and amounts to a majority of the NPC when dealing with SAPV systems. Additional importance can be considered since the DST is intended for MSEs that are likely to rely on smaller economical margins, and larger personal risks.

Batteries are replaced when they have gone through a certain amount of charging / discharging cycles, the method used in the DST is the Rainflow Counting Algorithm. The Rainflow Counting algorithm was initially to account for stress exposure in materials. One cycle is one instance of full stress exposure, a partial cycle is an instance of a partial stress exposure. The algorithm can be used to account for stress in batteries (You and Rasmussen 2011) and other appliances that go through similar wear.

1. Original Algorithm: (You and Rasmussen 2011)
2. Initiate a vector in encounter of a stress local minimum.
3. Note increase in stress during rainfall of vector
4. Count occurrences of ranges as one cycle
5. Sum the expended partial cycles for every stress level accounted for

Where n represents the number of bins chosen in the study; Nc(DOD) represents the number of consumed partial cycles at a given DoD level, derived by counting in the corresponding period; No(DOD) represents the maximum number of partial cycles that can be performed before battery failure at that DoD level.

Where ExpL denotes the expected lifetime of the BS, and Tp represents the length of the counting time period.

1. Implemented Algorithm:
2. Discover discharge valleys (can currently only occur after 8 consecutive hours of discharging)
3. Calculate cycles to failure for each occurring DoD:

This is the result of fitting a typical lead-acid battery cycles to failure vs. DoD characteristics. This equation has to be replaced or modified by the user.

1. Accumulate cycles to failure during simulation time.
2. Find replacement interval of batteries:

A requirement for finding the lifespan in years, is that the spendage of lifetime fractions are summed over one year precicely. This way we get the amount of years that the battery need. The expression from point 2 has to be replaced or modified if the user desire precision in the economic analysis.

1. Considerations

Every input related part of the DST should assume a generic form. This implementation assumes the that the rainflowCounter will keep counting for exactly one year. A more generic calculation is implemented in the rewritten DST as seen below.

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| Figure 4:1: Plotting DoD(Cycles To Failure) w/initial parameters.  There are not sufficient points of DoD in the intervall 0-20% to represent the Cycles to Failure accurately. |
|  |

The cyclesToFailure is calculated for every instance of DoD valley that occurs, which has an complexity of **O(n).** This resolution in cycle values might not be required considered the massive abstraction level of which we are operating. A future extension of the DST will at some point trigger far more occurences of DoD, before a simulation is considered complete. Users might want to input longer time series or change the 8 hour consecutiveness condition. In earlier versions of the algorithm (Downing and Socie 1982), the method proposed is preemptively generating a table of Cycles To Failure for every DoD percentage.

If the rate of change in DoD is not too close to zero, then the points of DoD will sufficiently describe the Cycles To Failure, as there are many values of DoD for each value of Cycles To Failure. By inspecting Figure 3:4, here the points of DoD percentage per cycles varies from 0.0001 to 0.01. It would not be safe generate an array with 1% resolution, the DoD rate is too low until about 20%. We can not guarantee that the DoD valleys wont occur in the 0%-20% range, even though it is less typical of a discharge cycle.

One solution is to increase the resolution of the DoD values to 0,1%, or perhaps smaller, in the precalculated array. The increased resolution will decrease computational gain. The DST overall complexity is , and the algorithm triggers a maximum of 3 times per day. Improvement of omputation-time when employing a precalculated array is too small, compared to the reduced precision of the implementation.

The 8-hour consecutiveness condition is similarly implemented in (Downing and Socie 1982), here the condition is 3 points. This can be understood as a lowpass filtering of the input. The physical consequences of potential “flutter” between cycles is neglectable. Additionally, charging cycles have daily periods, as seen in Figure 2:18 and Figure 2:19. The charging cycle follows the irradiation cycle and will not drop below 24 hours.

1. Logplot.m