Agent-Based Modelling to Inform Policy for Long-Term Electricity Generation Targets: ElecSIM a Toolkit

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ABSTRACT

Due to the threat of climate change, a shift from a fossil fuel based system to one based on renewable energy is required. To aid decision makers, we present the tool ElecSIM, which is an agent-based modelling framework used to examine the effect of policy on long term investment decisions. We present different techniques currently used to model long term energy decisions, and discuss why agent-based models are becoming an increasingly common tool to tackle this problem.

We explain why an open-source toolkit written in python is required, and how stochasticity improves reliability of the model. We describe the use of a scenario file which allows non-experts to rapidly prototype new ideas, and modularity which allows technical experts to add and remove features at will.

The model runs in yearly time steps, making assumptions based on empirical data on the impact of intermittent renewable energy. We present the dynamics of the system through scenario testing and provide validation.

Future work includes integrating different types of agent based learning for the bidding and investment process, utilising multi-agent reinforcement algorithms that can deal with a non stationary environment. We will use the yearly time-step as a baseline model for integration of a higher temporal and spatial resolution.

CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

KEYWORDS

datasets, neural networks, gaze detection, text tagging

1 INTRODUCTION

The world faces significant challenges from climate change and global warming. A rise in carbon emissions increases the risk of severe impacts on the world such as rising sea levels, species extinction, heat waves and tropical cyclones [2]. The scientific literature concurs that the recent change in climate is anthropogenic, with 97% of peer reviewed articles of this view [1].

To achieve carbon neutrality, the energy mix must shift from a largely fossil fuel based system, to one based on renewable energy. In essence, using solar, wind and tidal power to generate electricity and power homes, industry and transport [**?**].

For this to occur, a transition in electricity infrastructure is required. Moving from a centralised and homogenous fossil fuel-based system to a distributed system based on renewable energy and batteries. To better understand the risks and uncertainties surrounding this transition, and to model the potential actions that can be taken by policy makers, this paper presents ElecSIM, an open source agent-based modelling toolkit, written in python, which allows for the evaluation of alternative scenarios prior to implementation of policy.

This tool can be used by modelling experts to test policy outcomes under different scenarios and provide quantitative advice to policy makers. International agreements such as the Paris climate agreement, where nation states agreed on the goal of limiting the rise in global average temperature to well below $2°C$ above pre-industrial levels, mean that an open-source, reproducible and transparent model that can be taken to account by experts and understood by non-experts is of importance. This allows for the development of policies based on known assumptions, thorough testing and validation.

Optimisation models calculate an optimal cost pathway of investment in power plants over the long-term. However, many western democracies have purposely moved away from central control in the energy sector, which make the results of optimisation models difficult to implement. Agent-based models provide a solution to this by modelling heterogeneous actors with imperfect knowledge in a regulatory environment. The emergent behaviour of the agents can be observed under different policies such as a carbon tax.

Policy making in energy system comes with inherent risk. Decisions made can have large long term impacts and may be suboptimal. Power plants have high capital costs, long construction times, and operate over a long period. Therefore, errors made may be compounded, and can have effects well into the future.

This paper details our model, ElecSIM. Section 2 is a literature review of the models currently used in practice. Section 3 details the model and assumptions made. Section 4 details our results, and

explores ways in which ElecSIM can be used. We conclude the work in section 5

- We have developed a framework for evaluating alternative scenarios, prior to implementation of policy.
- Used by experts working in collaboration with policy makers.
- Importance of a transition in electricity infrastructure (Paris agreement, UK Climate change act)
- Importance of understanding effect of decisions made today on the future (limit of 1.5C by 2050)
- Introduce ElecSIM as a toolkit to inform long-term domestic policy questions in the electricity market.
- Ability to model the effects of carbon taxation, and the effect of different scenarios
- Talk about the need to model a non-stationary, dynamic system, with multiple interacting agents with imperfect information
- Requirement for an Open-Source, free Toolkit written in python. Low barrier of entry, and integration with existing python data analytics and machine learning techniques. Transparent, reproducible, and data made available. This allows for results to be open to greater criticism and better inform policy decisions.
- Simple model which matches real life behaviour for low complexity and therefore increases transparency.

2 LITERATURE REVIEW

- Agent Based Models - eg. EMCAS, PowerACE, EMLab: Leaves a requirement for an open source toolkit written in python. Many one-off models available, however difficult to apply to different scenarios.
- Bottom-up optimization models to find minimum cost of electricity system. [3]. eg. MARKAL/TIMES, MESSAGE. (These do not provide information on how to achieve a certain goal, particularly in a liberalized energy market. Or scenarios as to why a goal may not be achieved as the goal is assumed to be achieved.)
- Computational general equilibrium (CGE) models - Top-down macroeconomic models partial equilibrium model (energy supply, demand, cross-border trade, emissions)- Can be highly complex and difficult to understand. eg. NEMS, PRIMES.

3 ELECSIM

- Model can be modified through a single python scenario file which includes exogenous variables such as number of generation companies, power plants, power plant costs, tax and fuel prices, and demand.
- Architectural framework:
  - Agents are generation companies.
  - Generation companies initialized from government data. And randomized discount rate around a mean of 10% for nuclear power plants and 5.9% for other types of generators.
  - Costs of power plants taken from empirical data.

- Historical LCOE costs taken from data, with individual costs such as fixed operation and maintenance, construction and pre-development costs scaled linearly to match LCOE value. (This can be changed by user by specifying linear optimisation constraints).
- Historical Gas turbine and Coal plant efficiency taken from epa data.
- Variable operation and maintenance costs are stochastic to take into account differences in design types, preventative and corrective maintenance, labour costs and skill, asset and site management, health and safety and chance.
- Electricity demand taken from historical data and split up into 19 load segments.
- CO_2 prices, fuel Prices, demand growth are exogenous
- Fuel is bought by power producers each year at different prices, related to the standard deviation from historical data. This simulates different hedging strategies, luck and timing of fuel purchasing.
- Outages are modelled by assuming a 93% outage rate for fuel plants [?] and 97% outage for renewables. [?]
- Generation companies bid their short run marginal costs.
- Investments made on highest Net Present Value results. CO_2 price, fuel price and demand are predicted for the next year using linear regression. Expected price to sell predicted taking average of previous years. Investors will only invest if they have 25% of the total upfront costs. (the rest taken on by debt and equity as assumed by WACC value.)
- Intermittent power generators can only submit a certain percentage of their total capacity for each load segment. This percentage is matched with empirical data.
- Bids accepted by a centralised grid operator based on merit order.
- Assumptions:
  - Yearly time step
  - Renewables contribute to load curve of each demand segment matched with empirical data of typical wind and solar availability at each demand segment
  - Different discount rates per user (random)
  - Country initialized with full amount of power plants in country and total demand data considered
  - No curtailment of renewables
  - Imperfect foresight
  - Power plant construction and pre-development periods and costs modelled from UK Government BEIS data
  - Investments based on highest NPV using a single year to predict all years of power plant.
  - Agents predict next year's fuel, carbon and demand using linear regression and randomized look back period (between 3 and 6.)
  - Plants are dismantled after their lifetime, and only enter operation after pre-development/construction.
- Validation of model
  - Compare price duration curve
  - Compare power plant costs and NPV calculations
  - Look number of steps ahead to compare electricity mix and compare to actual (cross-validation)

- Performance metrics - Comparison with EMLab, PowerACE (15 minute run time)
  - Memory, disk size, runtime
  - Increase in time complexity with additional data.

4 SCENARIO TESTING

- Effect of different carbon tax on investments made.
- Effects of different demand scenarios. (High peaks, high growth, high reduction in demand)
- Effects of high fuel prices.
- Different costs of capital (eg. Borrowing for Nuclear of interest rate to equal 2% at government bonds rate, as opposed to 10% for private companies.)
- Different learning rates for renewable costs.
- The effect of long term carbon tax policy (eg. Carbon price known for next 25 years) vs short term changes in carbon tax.

5 CONCLUSIONS

- Requirement for agent based models based on imperfect information, liberalised energy markets
- Requirement for low barriers to entry open source model.
- Discuss results
- Future work:
  - Embedding multi-agent intelligence such as Genetic Algorithms, Q-learning and dynamic reinforcement learning
  - Raise spatial and temporal resolution.

6 INTRODUCTION

ACM's consolidated article template, introduced in 2017, provides a consistent LaTeX style for use across ACM publications, and incorporates accessibility and metadata-extraction functionality necessary for future Digital Library endeavors. Numerous ACM and SIG-specific LaTeX templates have been examined, and their unique features incorporated into this single new template.

If you are new to publishing with ACM, this document is a valuable guide to the process of preparing your work for publication. If you have published with ACM before, this document provides insight and instruction into more recent changes to the article template.

The "acmart" document class can be used to prepare articles for any ACM publication — conference or journal, and for any stage of publication, from review to final "camera-ready" copy, to the author's own version, with *very* few changes to the source.

7 TEMPLATE OVERVIEW

As noted in the introduction, the "acmart" document class can be used to prepare many different kinds of documentation — a double-blind initial submission of a full-length technical paper, a two-page SIGGRAPH Emerging Technologies abstract, a "camera-ready" journal article, a SIGCHI Extended Abstract, and more — all by selecting the appropriate *template style* and *template parameters*.

This document will explain the major features of the document class. For further information, the *LaTeX User's Guide* is available from https://www.acm.org/publications/proceedings-template.

7.1 Template Styles

The primary parameter given to the "acmart" document class is the *template style* which corresponds to the kind of publication or SIG publishing the work. This parameter is enclosed in square brackets and is a part of the documentclass command:

```
\documentclass[STYLE]{acmart}
```

Journals use one of three template styles. All but three ACM journals use the acmsmall template style:

- acmsmall: The default journal template style.
- acmlarge: Used by JOCCH and TAP.
- acmtog: Used by TOG.

The majority of conference proceedings documentation will use the acmconf template style.

- acmconf: The default proceedings template style.
- sigchi: Used for SIGCHI conference articles.
- sigchi-a: Used for SIGCHI "Extended Abstract" articles.
- sigplan: Used for SIGPLAN conference articles.

7.2 Template Parameters

In addition to specifying the *template style* to be used in formatting your work, there are a number of *template parameters* which modify some part of the applied template style. A complete list of these parameters can be found in the *LaTeX User's Guide*.

Frequently-used parameters, or combinations of parameters, include:

- `anonymous,review`: Suitable for a "double-blind" conference submission. Anonymizes the work and includes line numbers. Use with the \acmSubmissionID command to print the submission's unique ID on each page of the work.
- `authorversion`: Produces a version of the work suitable for posting by the author.
- `screen`: Produces colored hyperlinks.

This document uses the following string as the first command in the source file: \documentclass[sigconf,screen]{acmart}.

8 MODIFICATIONS

Modifying the template — including but not limited to: adjusting margins, typeface sizes, line spacing, paragraph and list definitions, and the use of the \vspace command to manually adjust the vertical spacing between elements of your work — is not allowed.

Your document will be returned to you for revision if modifications are discovered.

9 TYPEFACES

The "acmart" document class requires the use of the "Libertine" typeface family. Your TEX installation should include this set of packages. Please do not substitute other typefaces. The "lmodern" and "ltimes" packages should not be used, as they will override the built-in typeface families.

10 TITLE INFORMATION

The title of your work should use capital letters appropriately - https://capitalizemytitle.com/ has useful rules for capitalization. Use the `title` command to define the title of your work. If your work has a subtitle, define it with the `subtitle` command. Do not insert line breaks in your title.

If your title is lengthy, you must define a short version to be used in the page headers, to prevent overlapping text. The `title` command has a "short title" parameter:

\title[short title]{full title}

11 AUTHORS AND AFFILIATIONS

Each author must be defined separately for accurate metadata identification. Multiple authors may share one affiliation. Authors' names should not be abbreviated; use full first names wherever possible. Include authors' e-mail addresses whenever possible.

Grouping authors' names or e-mail addresses, or providing an "e-mail alias," as shown below, is not acceptable:

\author{Brooke Aster, David Mehldau}
\email{dave,judy,steve@university.edu}
\email{firstname.lastname@phillips.org}

The `authornote` and `authornotemark` commands allow a note to apply to multiple authors — for example, if the first two authors of an article contributed equally to the work.

If your author list is lengthy, you must define a shortened version of the list of authors to be used in the page headers, to prevent overlapping text. The following command should be placed just after the last \author{} definition:

\renewcommand{\shortauthors}{McCartney, et al.}

Omitting this command will force the use of a concatenated list of all of the authors' names, which may result in overlapping text in the page headers.

The article template's documentation, available at https://www.acm.org/publications/proceedings-template, has a complete explanation of these commands and tips for their effective use.

12 RIGHTS INFORMATION

Authors of any work published by ACM will need to complete a rights form. Depending on the kind of work, and the rights management choice made by the author, this may be copyright transfer, permission, license, or an OA (open access) agreement.

Regardless of the rights management choice, the author will receive a copy of the completed rights form once it has been submitted. This form contains LATEX commands that must be copied into the source document. When the document source is compiled, these commands and their parameters add formatted text to several areas of the final document:

- the "ACM Reference Format" text on the first page.
- the "rights management" text on the first page.
- the conference information in the page header(s).

Rights information is unique to the work; if you are preparing several works for an event, make sure to use the correct set of commands with each of the works.

13 CCS CONCEPTS AND USER-DEFINED KEYWORDS

Two elements of the "acmart" document class provide powerful taxonomic tools for you to help readers find your work in an online search.

The ACM Computing Classification System — https://www.acm.org/publications/class-2012 — is a set of classifiers and concepts that describe the computing discipline. Authors can select entries from this classification system, via https://dl.acm.org/ccs/ccs.cfm, and generate the commands to be included in the LATEX source.

User-defined keywords are a comma-separated list of words and phrases of the authors' choosing, providing a more flexible way of describing the research being presented.

CCS concepts and user-defined keywords are required for all short- and full-length articles, and optional for two-page abstracts.

14 SECTIONING COMMANDS

Your work should use standard LATEX sectioning commands: `section`, `subsection`, `subsubsection`, and `paragraph`. They should be numbered; do not remove the numbering from the commands.

Simulating a sectioning command by setting the first word or words of a paragraph in boldface or italicized text is **not allowed.**

15 TABLES

The "acmart" document class includes the "booktabs" package — https://ctan.org/pkg/booktabs — for preparing high-quality tables.

Table captions are placed *above* the table.

Because tables cannot be split across pages, the best placement for them is typically the top of the page nearest their initial cite.

Table 1: Frequency of Special Characters

Non-English or Math	Frequency	Comments
Ø	1 in 1,000	For Swedish names
π	1 in 5	Common in math
$	4 in 5	Used in business
Ψ_1^2	1 in 40,000	Unexplained usage

To ensure this proper "floating" placement of tables, use the environment **table** to enclose the table's contents and the table caption. The contents of the table itself must go in the **tabular** environment, to be aligned properly in rows and columns, with the desired horizontal and vertical rules. Again, detailed instructions on **tabular** material are found in the *LaTeX User's Guide*.

Immediately following this sentence is the point at which Table 1 is included in the input file; compare the placement of the table here with the table in the printed output of this document.

To set a wider table, which takes up the whole width of the page's live area, use the environment **table*** to enclose the table's contents and the table caption. As with a single-column table, this wide table will "float" to a location deemed more desirable. Immediately following this sentence is the point at which Table 2 is included in the input file; again, it is instructive to compare the placement of the table here with the table in the printed output of this document.

16 MATH EQUATIONS

You may want to display math equations in three distinct styles: inline, numbered or non-numbered display. Each of the three are discussed in the next sections.

16.1 Inline (In-text) Equations

A formula that appears in the running text is called an inline or in-text formula. It is produced by the **math** environment, which can be invoked with the usual \begin . . . \end construction or with the short form $ . . . $. You can use any of the symbols and structures, from α to ω, available in LaTeX [?]; this section will simply show a few examples of in-text equations in context. Notice how this equation: $\lim_{n\to\infty} x = 0$, set here in in-line math style, looks slightly different when set in display style. (See next section).

16.2 Display Equations

A numbered display equation—one set off by vertical space from the text and centered horizontally—is produced by the **equation** environment. An unnumbered display equation is produced by the **displaymath** environment.

Again, in either environment, you can use any of the symbols and structures available in LaTeX; this section will just give a couple of examples of display equations in context. First, consider the equation, shown as an inline equation above:

$$\lim_{n\to\infty} x = 0 \tag{1}$$

Notice how it is formatted somewhat differently in the **displaymath** environment. Now, we'll enter an unnumbered equation:

$$\sum_{i=0}^{\infty} x + 1$$

and follow it with another numbered equation:

$$\sum_{i=0}^{\infty} x_i = \int_0^{\pi+2} f \tag{2}$$

just to demonstrate LaTeX's able handling of numbering.

17 FIGURES

The "figure" environment should be used for figures. One or more images can be placed within a figure. If your figure contains third-party material, you must clearly identify it as such, as shown in the example below.

Figure 1: 1907 Franklin Model D roadster. Photograph by Harris & Ewing, Inc. [Public domain], via Wikimedia Commons. (https://goo.gl/VLCRBB).

Your figures should contain a caption which describes the figure to the reader. Figure captions go below the figure. Your figures should **also** include a description suitable for screen readers, to assist the visually-challenged to better understand your work.

Figure captions are placed *below* the figure.

17.1 The "Teaser Figure"

A "teaser figure" is an image, or set of images in one figure, that are placed after all author and affiliation information, and before the body of the article, spanning the page. If you wish to have such a figure in your article, place the command immediately before the \maketitle command:

```
\begin{teaserfigure}
  \includegraphics[width=\textwidth]{sampleteaser}
  \caption{figure caption}
  \Description{figure description}
\end{teaserfigure}
```

Table 2: Some Typical Commands

Command	A Number	Comments
\author	100	Author
\table	300	For tables
\table*	400	For wider tables

18 CITATIONS AND BIBLIOGRAPHIES

The use of BIBTEX for the preparation and formatting of one's references is strongly recommended. Authors' names should be complete — use full first names ("Donald E. Knuth") not initials ("D. E. Knuth") — and the salient identifying features of a reference should be included: title, year, volume, number, pages, article DOI, etc.

The bibliography is included in your source document with these two commands, placed just before the \end{document} command:

    \bibliographystyle{ACM-Reference-Format}
    \bibliography{bibfile}

where "bibfile" is the name, without the ".bib" suffix, of the BIBTEX file.

Citations and references are numbered by default. A small number of ACM publications have citations and references formatted in the "author year" style; for these exceptions, please include this command in the **preamble** (before "\begin{document}") of your LATEX source:

    \citestyle{acmauthoryear}

Some examples. A paginated journal article [?], an enumerated journal article [?], a reference to an entire issue [?], a monograph (whole book) [?], a monograph/whole book in a series (see 2a in spec. document) [?], a divisible-book such as an anthology or compilation [?] followed by the same example, however we only output the series if the volume number is given [?] (so Editor00a's series should NOT be present since it has no vol. no.), a chapter in a divisible book [?], a chapter in a divisible book in a series [?], a multi-volume work as book [?], an article in a proceedings (of a conference, symposium, workshop for example) (paginated proceedings article) [?], a proceedings article with all possible elements [?], an example of an enumerated proceedings article [?], an informally published work [?], a doctoral dissertation [?], a master's thesis: [?], an online document / world wide web resource [? ? ?], a video game (Case 1) [?] and (Case 2) [?] and [?] and (Case 3) a patent [?], work accepted for publication [?], 'YYYYb'-test for prolific author [?] and [?]. Other cites might contain 'duplicate' DOI and URLs (some SIAM articles) [?]. Boris / Barbara Beeton: multi-volume works as books [?] and [?]. A couple of citations with DOIs: [? ?]. Online citations: [? ? ?].

19 ACKNOWLEDGMENTS

Identification of funding sources and other support, and thanks to individuals and groups that assisted in the research and the preparation of the work should be included in an acknowledgment section, which is placed just before the reference section in your document.

This section has a special environment:

    \begin{acks}

    ...
    \end{acks}

so that the information contained therein can be more easily collected during the article metadata extraction phase, and to ensure consistency in the spelling of the section heading.

Authors should not prepare this section as a numbered or unnumbered \section; please use the "acks" environment.

20 APPENDICES

If your work needs an appendix, add it before the "\end{document}" command at the conclusion of your source document.

Start the appendix with the "appendix" command:

    \appendix

and note that in the appendix, sections are lettered, not numbered. This document has two appendices, demonstrating the section and subsection identification method.

21 SIGCHI EXTENDED ABSTRACTS

The "sigchi-a" template style (available only in LATEX and not in Word) produces a landscape-orientation formatted article, with a wide left margin. Three environments are available for use with the "sigchi-a" template style, and produce formatted output in the margin:

- sidebar: Place formatted text in the margin.
- marginfigure: Place a figure in the margin.
- margintable: Place a table in the margin.

ACKNOWLEDGMENTS

REFERENCES

[1] John Cook, Dana Nuccitelli, Sarah A Green, Mark Richardson, Bärbel Winkler, Rob Painting, Robert Way, Peter Jacobs, and Andrew Skuce. 2013. Environmental Research Letters Quantifying the consensus on anthropogenic global warming in the scientific literature Quantifying the consensus on anthropogenic global warming in the scientific literature. *Environ. Res. Lett* 8 (2013), 24024–7. https://doi.org/10.1088/1748-9326/8/2/024024

[2] IPCC. 2014. Foreword, Preface, Dedication and In Memoriam. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (2014), 1454. https://doi.org/10.1017/CBO9781107415416 arXiv:arXiv:1011.1669v3

[3] Stefan Pfenninger, Adam Hawkes, and James Keirstead. 2014. Energy systems modeling for twenty- first century energy challenges. *Renewable and Sustainable Energy Reviews* 33 (2014), 74–86. https://doi.org/10.1016/j.rser.2014.02.003

A RESEARCH METHODS

A.1 Part One

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Morbi malesuada, quam in pulvinar varius, metus nunc fermentum urna, id sollicitudin purus odio sit amet enim. Aliquam ullamcorper eu

ipsum vel mollis. Curabitur quis dictum nisl. Phasellus vel semper risus, et lacinia dolor. Integer ultricies commodo sem nec semper.

A.2 Part Two

Etiam commodo feugiat nisl pulvinar pellentesque. Etiam auctor sodales ligula, non varius nibh pulvinar semper. Suspendisse nec lectus non ipsum convallis congue hendrerit vitae sapien. Donec at laoreet eros. Vivamus non purus placerat, scelerisque diam eu, cursus ante. Etiam aliquam tortor auctor efficitur mattis.

B ONLINE RESOURCES

Nam id fermentum dui. Suspendisse sagittis tortor a nulla mollis, in pulvinar ex pretium. Sed interdum orci quis metus euismod, et sagittis enim maximus. Vestibulum gravida massa ut felis suscipit congue. Quisque mattis elit a risus ultrices commodo venenatis eget dui. Etiam sagittis eleifend elementum.

Nam interdum magna at lectus dignissim, ac dignissim lorem rhoncus. Maecenas eu arcu ac neque placerat aliquam. Nunc pulvinar massa et mattis lacinia.