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A Holistic Implementation of Data Science in Clean Energy Engineering Education

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Introduction

Advances in technology and economic expansion require increased use of energy. At the same time, technology has significantly improved energy efficiency and allows exploitation of a variety of diverse and plentiful sources of clean energy. This has led to a clean energy revolution, as stated by the Department of Energy [1]. We are witnessing expansion of economic activities driven by advances in clean energy technologies, which is in turn leading to new technological breakthroughs [2].
It is predicted that by 2040, artificial intelligence (AI) applications, in combination with other technologies, will become prevalent in almost every aspect of life, including but not limited to energy, healthcare, and transportation. Empowered by simultaneous increases in high-quality data, computing resources and communication infrastructure, AI will challenge societies to gain most of the benefits and at the same time reduce negative social effects [3].

This paper describes the development of a program that provides students with knowledge and skills in various aspects of energy, economics, and data science, calling attention to the areas in the program impacted by the newly developed courses, and expands on several activities designed to engage students through active learning and research experiences.

Master of Science in Data Science and Analytics (MS DSA) at SUNY Buffalo State

Addressing growing demand for AI and data science professionals, MS DSA was developed at SUNY Buffalo State in 2019 with support of Performance Improvement Grant from the State University of New York (SUNY) The program is housed in the Interdisciplinary Unit created specifically for this purpose and was initiated by the faculty from Mathematics and Computer Information Systems (CIS). The program targets students and over 20 local industries, government and non-profits and has been successful in attracting over 60 students and serving such companies and organizations including but not limited to IBM Buffalo Innovation Center, Army Corps of Engineers, Wells Fargo, Thermo Fisher Scientific, Aurubis, Rich Products, Packhouse Technology Solutions, CUBRC, M&T Bank, and Roswell Park Cancer Institute. One of the main features of the program is the experiential component with an emphasis on developing project management and professional communication skills.

The original DSA program currently comprises of ten courses (for a total of 30 credit hours) including the following: (1) four required courses: MAT 646 Introduction to Statistics for Data Science; MAT 616 Elements of Mathematics, Programming and Computer Science to Data Science; CIS 512 Introduction to Data Science and Analytics; CIS 600 Machine Learning for Data Science; (2) five elective courses to be selected from BUS 519 Communication for Leaders and Managers; DSA 501 Data Oriented Computing and Analytics; DSA 650 Data Strategy and Governance; GES 584 Geospatial Programming; PSM 601 Project Management for Math and Science Professionals and from other available courses by advisement such as GEG 585 Interactive and Web-Based Mapping; COM 547 Data Analytics for Strategic Communication;

HEA 730 Data Visualization and Storytelling; BIO 587 Bioinformatics; BIO 670 Advanced Biostatistical Analysis; and (3) DSA 690 Internship.

Students enrolled in the program are expected to complete four required courses within their first two semesters. These serve as the fundamental building blocks for the more interdisciplinary and data science-infused elective courses.

Clean Energy Curriculum Development

In recent years there has been a growing awareness about aging utilities infrastructure and significant retirements are anticipated, placing an increasing demand for qualified graduates to enter the workforce [4]. Significant Government and industry funding are being targeted towards modernization of existing electric power system. These efforts are critical to achieving renewable energy development, electric vehicle adoption, and energy efficiency improvements. To address these challenges requires partnerships among academia, government, and industry to ensure that students have access to internships and that the curriculum aligns with industry needs.

In 2019 SUNY Buffalo State received performance improvement funding from the State University of New York (SUNY) to develop curriculum and laboratory infrastructure in Clean Energy to address the needs of local industries. A Community of Practice (CoP) was formed within SUNY system and the Clean Energy Consortium was established to coordinate the efforts of several institutions in the development and dissemination of courses and programs and being a platform to exchange ideas, complement what is being done at other campuses, and leverage each other.

In consultation with local industries several courses were developed at SUNY Buffalo State at the undergraduate and graduate levels. These include ENT 340, Building Information Modeling; ENT 350, Electric Codes and Standards, ENT 360, Smart Buildings and Energy Efficiency; ENT 221, Nanoscale Engineering; ENT 622, Machine Learning for Materials Science in Clean Energy; and DSA 621, Data Science Tools in Energy Engineering. Several teaching laboratories were improved with the addition of new equipment and computational software.

Initial planning of this proposal called for the development of a certificate program in clean energy directed towards engineers employed by industrial partners. As the program developed, industry partners indicated preference for an advanced degree in lieu of an undergraduate certificate, hence several courses were developed for graduate-level.

Clean Energy Option of MS DSA

Significant government and industry strategic investments are being targeted towards achieving renewable energy development, energy efficiency improvements, energy delivery infrastructure, data science, and AI among others. AI dependent industries and organizations of the future will likely need to possess and manage immense amounts of data for efficient and competitive operations. Data has been described as the world’s most valuable resource [3]. As stated in Harvard Data Science Review, “Data science is seen as a key enabler for technologies that help decarbonize global energy use. However, the energy sector continues to struggle to attract and train enough data scientists. The primary reason for this is the lack of emphasis on data science in most graduate programs in energy engineering, and the high barriers of entry for data scientists from other sectors" [5]. This requires education of qualified energy professionals skilled in AI and its main vehicle – data science.

Based on industry feedback and national and international trends in both clean energy and data science [1,3,5, 6], a Clean Energy option was added to the existing MS DSA program. This option was created as a collaboration between the Interdisciplinary Unit in Data Science and Engineering Technology department at SUNY Buffalo State. The overall educational goal of this option is to provide students with an understanding of data science and clean energy analytics.

The option is designed for students with background in STEM areas who have an interest in clean energy and are interested and inspired by the use of data science to solve sustainability problems. It offers a broad understanding of accelerated pace of science and engineering, energy systems, economics, data science and analytics tools in solving complex multidisciplinary energy-related problems.

Clean Energy option of Data Science and Analytics MS program is tailored to best meet individual students' educational background and professional goals. The curriculum includes courses exploring and mining all the aspects of the data lifecycle using mathematics, statistics, machine learning, database management, data visualization, programming, business intelligence, energy economics, the smart grid, energy engineering, and fundamental physics and devices relating to renewable energy. Upon completion of the program, students are able to: analyze and interrogate data; manage energy data including organization, storage, cleaning and manipulating data using appropriate software and programming languages (Python, SQL, SAS, Excel, R, SPSS, Tableau); and visualize and effectively communicate results using dashboards, charts, graphs, written and oral reports.

The Clean Energy option within the MS DSA program includes several specialized courses. Four courses for this option are selected from the following: ENT 581, Distributed Renewable Generation and Storage; ENT 582, Operation and Management of Modern Grid; DSA 621, Data Science Tools in Energy Engineering; ENT 622, Machine Learning for Materials Science in Clean Energy; ECO 660, Cost Benefit Analysis; and ECO X55, Energy and Environmental Economics (being currently redesigned to graduate level course).

Because several of these courses have traditionally been offered within a department rather than in this new interdisciplinary program (e.g., ENT 581, ENT 582, ECO 660, and ECO X55), they are currently being redesigned to be more interdisciplinary in nature and include the data science component. However, DSA 621 and ENT 622 were developed with the intent of being offered specifically for Clean Energy option and were the first specialized offerings for the program since Fall 2021.

Courses and Content

Clean Energy option courses are all 3-credit hours courses and are covering the following areas:

ENT 581 (*Distributed Renewable Generation and Storage*) introduces renewable and efficient electric power systems. It encourages self-teaching by providing numerous practical examples requiring quantitative analysis. Topics include historical, regulatory, and utility industry perspectives of the electric system as well as most of the electricity, thermodynamics, and engineering economics background needed to understand new power technologies.

ENT 582 *(Operation and Management of Modern Grid)* provides comprehensive understanding of smart grid as needed for stakeholders to enable them to develop systems prospective of Smart Grid and its technologies, increase modeling of Smart Grid from multiple perspectives, to increase economic understanding and decision making around current and future technologies, to integrate the role of policy and politics in the advancement of Smart Grid over time, and to analyze basic subsystems of the Smart Grid.

ECO X55 *(Energy and Environmental Economics (being redesigned for a graduate 500 or 600 level)* deals with micro- and macroeconomic activity imposed by the availability of energy resources and by environmental considerations. Alternative policy strategies relating to energy and the environment are evaluated in terms of their economic impact.

ECO 660 *(Cost Benefit Analyses)* covers methods of estimating and comparing benefits and costs for the purpose of policy analysis and project evaluation in the public, private, and not-for-profit spheres. Topics include present-value calculations and estimating monetary values of nonmarket transaction, qualitative benefits, and costs, such as health, education, environmental impact, recreation, and quality of life.

DSA 621 *(Data Science Tools in Energy Engineering*) covers tools and techniques needed to collect, clean, analyze and present data specific to the field of Energy Engineering in large datasets; statistical models to describe data; visualization of data; spreadsheets; databases; Python.

ENT 622 *(Machine Learning for Materials Science in Clean Energy)* covers broad guidelines and best practices regarding obtaining and treatment of data in materials science and device physics related directly to Clean Energy. Feature engineering, model training, validation, evaluation, and comparison. Includes interactive Jupyter notebooks with example Python code to demonstrate important concepts, workflows, and best practices in the field.

As DSA 621 and ENT 622 courses were specifically developed for the program (while other courses in the option were adapted to it), more details on their content are presented in Tables 1 and 2.

Table 1. Course Content and Student Learning Outcomes of DSA 621 Data Science Tools in Energy Engineering

Students Learning Outcomes: 1. Analyze data from Engineering using Data Science tools and subject expertise.

2. Explain Data Science tools for statistical Engineering data models to a general audience.
3. Select most appropriate Data Science method for a required dataset.
4. Justify acquisition and preparation of datasets for analysis.
5. Create visualizations, dashboards and reports of information mined from engineering datasets.
6. Explain data integrity, governance, storage maintenance using Data Science tools and standards.

Course Content:

I. Overview of software currently available for various DSA tasks
    a. Spreadsheets: Excel, Google Spreadsheets, or other software to easily visualize relatively small tables of data.
    b. Data wranglers: Python, R, SAS, or other current software to easily manipulate raw data into appropriate format for further analysis.
    c. Data analysis: Python, R, SAS, or other current software to easily create descriptive and predictive models
    d. Data storytelling and visualization: Excel, Python, Tableau or other current software to easily communicate information mining results from data analysis in reports, graphics and dashboards.

II. Overview of Data repositories for Engineering and Data collection
    a. Finding and connecting to Data. API protocols.
    b. Current data repositories in Engineering, Clean Energy, Material Science, and related fields.
    c. Data governance; integrity, security, privacy, ownership, stewardship.
    d. Examining data format; csv, xml, Json.
    e. Relational vs non-relational databases; concepts and definitions.
    f. Examining data type; date, string, numeric.
    g. Examining data encoding; ASCII, UTF-8.
    h. Data sets warehousing; data storage and maintenance.

III. Data preparation, cleaning and experiment design
    a. Joining Data
    b. Data Wrangling from the Subject Matter Expert (SME) point of view
    c. Examining the data as a SME for particular projects
    d. Cleaning up the data as a SME for particular projects
    e. Feature engineering as a SME for particular projects

IV. Organizing and describing the data for Engineering use
    a. Statistical models; standard deviation, range, distributions
    b. Grouping of data; extracting tables with desired properties.
    c. Visualizing data from relational and non-relational databases.

V. Storytelling with Data
    a. Creating graphics
    b. Creating dashboards
    c. Creating reports

Table 2. Course Content and Student Learning Outcomes of ENT 622 Machine Learning for Material Science in Clean Energy

Student Learning Outcomes:

1. Analyze the fundamentals of materials properties and device physics that drive solar energy conversion and battery storage in the field of Clean Energy.
2. Generate best practices of data wrangling.
3. Interpret the methodologies of splitting datasets.
4. Formulate classical and statistical machine learning approaches including regression analyses, support vector machines, k-nearest neighbors, and decision trees; produce a working knowledge of utilizing neural networks, evaluating models, exporting models, and avoiding overfitting.
5. Analyze visualization techniques such as t-distributed stochastic neighbor embedding, uniform manifold approximation and projection, and elemental prevalence mapping to investigate dataset imbalance and bias.
6. Validate how to generate peer-review publication-ready, reproducible work.
7. Produce critical thinking and creative problem solving in working with materials datasets in Clean Energy.
8. Organize and execute effectively in teams.

Course Content

I. Overview: Clean Energy and Machine Learning
    a. Close to home: The Clean Energy landscape of XXX
    b. Fundamentals of Materials properties in Solar Devices and Batteries
    c. Solar Cell Device Physics and Battery Physics
    d. Materials Informatics and Machine Learning
II. Data Wrangling
    a. Data extraction and loading
    b. Examining, Processing and Cleaning up data
III. Splitting datasets
    a. Train
    b. Validation
    c. Test
IV. Machine Learning models
    a. Regression Analyses
    b. Support vector machines
    c. k-nearest neighbors
    d. Decision trees
    e. Overfitting and selection bias
V. Visualization tools and techniques:
    a. Matplotlib and other Python libraries.
    b. Tableau.
    c. Useful techniques to investigate data imbalance and bias:
        i. t-distributed stochastic neighbor embedding

ii. Uniform manifold approximation and projection (UMAP)
iii. Elemental prevalence mapping
d. Visualization Tool for Atomic models (VITAL)
VI. Work in teams: Methods to produce peer-review, publication-ready, reproducible work

Mandatory Experiential Components

Key elements driving success in the program include a required student internship and mentorship opportunities with partners that the program option directors have historically developed and sustained. These include local Clean Energy partners in industry, power utility companies (National Fuel, New York Power Authority (NYPA), National Grid), government laboratories (e.g., Brookhaven National Lab) and county as well as city government offices (Erie County and City of Buffalo).
Hands-on experiences have been shown to help develop students' interests in research and help them confirm their ultimate job choice in a STEM field [7, 8]. To that end, beyond the external opportunities listed above, the program directors with inherent expertise in different aspects of clean energy research including computational/theoretical work, experimental work, data analytics/machine learning, and applications (including at the system-level), and finally in economics and policy, are working together to include substantive research components within the required and elective courses [9 -14], thereby making the overall program much more cohesive.

The program option directors are flexible and continually evolve on this critical research aspect of the program to successfully execute the core interdisciplinary theme of the project. To this end, DSA 621 and ENT 622 are currently being further developed to have students produce a publication-quality research paper and conference presentation at the end of the courses.
By the end of the program the students are expected to have a diversified skillset that is well beyond classroom knowledge – this will allow them to become effective and efficient in technical and/or managerial related roles in the Clean Energy industry while giving them a global perspective of impacts of technologies and policies in the Clean Energy field.

Laboratory Facilities and Equipment

The courses in the Clean Energy option of MS DSA are taught in well-equipped spaces with computational and experimental hardware and software. These facilities are available for the MS DSA – Clean Energy option students for select projects within the courses offered.
The computational facility entails six PowerEdge R740 Rack Servers (128 TB space and 1.53 TB memory) with associated Powerswitch connectivity, keyboard video mouse (KVM) and other setup units. The servers can be remotely and parallel-accessed by students from various on-campus computer facilities (described below). These facilities are used for computational work including Density Functional Theory (DFT) and Molecular Dynamics (MD). Experimental equipment in this area includes hot plate with magnetic stirrer, muffle furnace, desktop spin coater, and solar simulator and external quantum efficiency measurement setup.
The data science aspect of the program utilizes the High-Performance Computing Lab (Hiperc). It has collaboration tools so that students can easily share screens, use tools and resources for

networking, and access servers and computer/networking components of the lab. Hiperc is especially designed to support research projects among small groups of students.

The Smart Grid lab contains state-of-the-art equipment that supports all aspects of power generation, delivery, and utilization including distributed energy resources (DER), microgrids, and nano-grids. The setup of a solar emulator together with the micro and nano-grids employs block-chain models that are utilized for making economic decisions in solar markets as well as RTDS NovaCor unit for real-time digital simulation of the grid.

Students' and Industry Reflections

Since MS in DSA is three years old and its Clean Energy option is in its inaugural year, the pool of students for feedback was comprised of all five students currently taking courses in this option as of the time of writing. Remarks from theese students received as part of course evaluations as well as comments voluntarily submitted, are very enthusiastic and positive:

"In addition to learning new things in the classroom, I really like that there is a lot of effort put into program-related activities outside of the classroom as well. There are seminars with professionals in the industry, networking events, and study groups. It helps to connect with others in the field to bounce ideas off one another and see how what I'm learning in class applies to the real world."

"Overall, I have been very satisfied and happy with my decision to be part of the DSA program. It has helped me to be more confident in the approaches I take toward reports and analysis, while continuing to help me build skills needed to reach my career goals."

"[My favorite part of the program is] the community that has been created. Everyone is excited about this field, and it seems to be expanding."

"There is a significant demand for data analytics in every company and getting formal knowledge is key to success and better paying jobs."

"I found the course (DSA 621) very interesting as a whole. It taught me how we can deconstruct claims presented by the news, and articles online about energy engineering and find out for ourselves if the data presented matches the data we found. We used current events to learn about deriving useful data from otherwise over-saturated spread sheets. From this class, I have gained new ways to find, interpret, and present useful material for other class projects and give insight on the reality of what is occurring when figures are thrown at you in the media. We reviewed different types of graphs and found how different data points can impact trend lines through data manipulation. Additionally, I learned new tools to use on excel spread sheets. I found the class to be extremely compelling, identifying and analyzing data within current events".

Industry feedback includes the following:

"Data plays an integral role in the energy sector, driving almost every facet of the industry. With data analytics, organizations in this critical sector can learn to get the most out of their data and better serve their communities through optimal energy utilization and process refinement. As a cybersecurity professional at National Fuel, I see every day how data plays a key role in protecting our infrastructure as we provide energy to our communities in Western New York and Pennsylvania. MS DSA Clean Energy option at SUNY Buffalo State provides a better insight for our engineers to efficiently use methods and tools to realize these objectives".

"National Grid is committed to shaping a sustainable economy for all, in partnership with others in our industry and beyond. Our plan is to achieve Net Zero by 2050 in the US. Our environmental commitments include reducing Sulfur Hexofluoride (SF6) emissions from our operations 50% by 2030 from a 2019 baseline and achieve net zero by 2050 in the US by eliminating SF6 emissions. In order to meet the 2030 emissions reduction goal, SF6 leaks must be managed and repaired quickly but we also need to reduce the fleet of present SF6 circuit breakers and future breakers with non-SF6 alternatives. Using the skillset attained at MS DSA program at SUNY Buffalo State, we utilize data analytics tools to predict attainability of emission reduction goal by future replacements and additions of non-SF6 alternative breakers".

"Data Science and Analytics is essential in creating an accurate road map to a goal of 100% clean energy and zero carbon emissions within New York State. The New York Independent System Operator (NYISO) procures bulk power in the Day Ahead and Real Time Market providing reliable low-cost energy to NY State. The NYISO is comprised of engineers, operators, analysts, and economists who continuously study the electric grid's everchanging condition throughout the day in efforts to procure clean energy while maintaining a reliable grid. This task is not easy and would be nearly impossible if it were not for data. Data Science and Analytics at Buffalo State are vital to predicting the electric grid impact/response due to load swings, systems condition changes, weather pattern changes, and line trips – all of which can impact clean energy generation and the reliability of the electric grid. Data Science and Analytics tools which include feedback loops as taught at SUNY Buffalo State allow analyses of incremental and iterative electric grid changes which in turn can maximize clean energy generation and increase grid reliability".

Program and option directors intend to evaluate student learning outcomes in future semesters and will make revisions to the option as necessary to ensure that students meet the knowledge, abilities, and skills identified by industry.

Conclusions

While power and energy industry are in chronic need of energy data scientists, most energy engineering programs are not producing them. Moreover, it is quite difficult for the energy industry to compete with other analytics-savvy industries in recruiting data scientists [5].

Universities and utilities have to work together to make this happen [16]. Moreover, strong collaboration between universities is highly desirable to create this new "product line" of energy data scientists and to enrich their programs with relevant course content [5]. Very few programs of this kind are available and to the best of the authors' knowledge they are mostly located in Europe [5]. As an example, Energy Systems and Data Analytics program at University College London [15] is quite similar in its scope and intent and will serve as an inspiration for future enhancement of Clean Energy option in described MS DSA. However, it does not have required internship and experiential component, which is an important feature of the program at SUNY Buffalo State.

The vision of the program at SUNY Buffalo State is to provide students a holistic educational experience through the MS in DSA – Clean Energy option. Clean energy workers need to be as prepared and competitive as possible, and the given program aims to address the current and future industry needs by creating a generation of specialists with fluency in a range of related disciplines. Students in this program will develop critical skill sets needed to be actively and meaningfully engaged in the highly impactful fields of energy, while having expertise in engineering, data science, and economics. The graduates will be equipped to understand and lead conversations surrounding data-driven decisions on clean energy regulation and policy decisions while also being able to work directly in pure engineering positions as well as data-centric positions. The program overall and its Clean Energy option were developed with strong industry guidance and feedback and is flexible enough to adjust to ever-changing realities in their respective fields.

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