Reflections and a Vision Toward a Sustainable Education in Electrical Engineering: Next generation of electrical engineers

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Reflections and a Vision Toward a Sustainable Education in Electrical Engineering: next generation of electrical engineers

Marcelo Godoy Simões, Paulo F. Ribeiro

1. Introduction

Technology shapes the way we live, and its power is old and new – as is the wisdom we need to visualize, design, build and use it well, aware of its importance for social development. Designing and using Electro-Technology and Processing for Electrification is an implicit and intrinsic mission of every Electrical and Electronics Engineer. The field evolved, as the electrotechnology of the 20th century became the electronics, and the software is now implemented on silicon-based microprocessors and microcontrollers, data might be on the cloud, while the real-time control maybe a very small, embedded circuit. The 21st century brought the reality of distributed computing, cloud-based services, ultrafast real-time execution of control with digital twin, incorporation of highly sophisticated mathematical models, and the advent of artificial intelligence. It is now clearer than ever, that resources are not eternally lasting, and electrification is also a process of empowering individuals, and is bringing change to our modern society. In this paper the authors describe how the past has shaped our present, where we are at right now, forecast future development and give suggestions for next generation of Electrical Engineers. The authors have discussed a formative approach based on the history and philosophy of Electrical Engineering and Electrification, with a basis on a survey with professionals in the area [1]; those are further developed in this paper.

For individuals born today who have the potential to join a university in about 18 to 20 years, there will also be young professionals who will be in charge of preparing them. All these great people will support a sustainable, renewable, circular-economy-based electrification in the 21st century. These include educators, professionals, industry and the academia of today. Transportation and off-grid sectors are aligned from a technical perspective, and there is synergy in related areas such as business, environmental, and geopolitics. It is important to have our elected officials adopt social and policy topics, with tools and wisdom, in order to keep building our education and actions for societal inclusion and sustainability.

One of the pillars for motivating academia and industry is to build a workforce that can meet the expected future demand in the electrification sector. On the other hand, to motivate individuals, it is necessary to pursue a more philosophical path, making students choose something that aligns with their strengths and passions.

A well-rounded education should be multidisciplinary, in order to give breadth, but also allowing in-depth discoveries. Teaching should be fun and at the same time serious, giving the pupil immediate value and at the same time ringing bells for further inquiries. The authors of this paper have an optimistic expectation that motivating the current young generation of future leaders will need to be met with developing solutions targeted to make our planet sustainable, fair, just, and using our energy resources in an optimum way. Markets that require integration of data analysis, digital and communication technologies will be the most attractive ones.

2. Further Educational Developments in Electrification

In order to find out more about the status of Electrification Education, three additional surveys were conducted for this paper. We obtained very insightful data that still has a great deal of information for further analysis [the survey files are available upon request]. The collected information can support substantial case studies to move forward into an Electrification Education for the 21st century. How could we design a curriculum for second, third and additional layers of courses in electrification, which learning should be emphasized. The survey was organized into two sections; the first one is topical and structural regarding a curriculum that the respondent has experienced during her or his education. This first part is easier to graph and get many pie charts or illustrative data, whereas the second part is relational, i.e. the respondent has the maturity after so many years after graduation and actively working that she or he can identify relationships, pre and post learning experiences, and even suggest other paths. This second part is qualitative, with a lot of unstructured responses that have to be ready to evaluate based on the ontology concerned with what is true or real as regarding education, or epistemology, as 'theory of knowledge'. Then one can know how to find a proper strategy to implement a revised and transforming curriculum.

What courses did you take that were important for your first initial jobs? How different is today for a first job for a fresh graduated Electrical Engineer?

1) Probably you are not in the first job now, you are senior, with more experience, credentials, and responsibilities, so, although the current times are not the same as before, which IMMUTABLE courses and experiences, should be kept, maybe enhanced, but which topics and courses any good Electrical Engineering program must have today that were in the past, probably now can be enhanced with some pedagogical twists, but at the core, the science and engineering were important and continue to be important now and probably for the future ?

2) If you have either a Master or a PhD, or maybe both, please make a similar reflection of courses that were important for you, what you see are important today, and which ones should continue to be taught as core courses for excellence in an EE graduate program?

3) Now let us try to be a little more selective, below we have several possible pathways inside an EE curriculum, please select two, even if you find three to be very important, select your BEST TWO pathways that you believe are important to invest in a new education paradigm. If none of below fits what you want, please write yourself a description of what you believe should be TWO pathways of knowledge, i.e., on top of the core courses that you believe are immutable, which ones are important for the Electrical Engineering and Electrification of the 21st century. When you select below, please write a short paragraph of why you chose that Pathway.

- Applied electromagnetics, microwave circuits, antennas and radio-propagation,
- High-frequency circuits, electromagnetism
- Wireless networks, software-defined-radio, network security, cyber-security
- Statistical signal processing, machine learning, cyber-physical systems, artificial intelligence,
- Controls, Mathematics of large linear systems
- Wind turbines, hydropower turbines, thermodynamics, fluids
- Computer science, computer engineering, industrial automation

- Batteries, fuel cells, solar cells, materials and semiconductors

4) Complementing the previous question, now please look at this description of courses, topics, that are usually relevant to modern Electrification, please make a reference, add your thoughts, align the next bullet to the previous two pathways that you have chosen. If there is anything missing in the following bullet, please write in the box how you see the convolution of those two pathways with this power-electronics/power-systems area of electrification and sustainability:

- Power electronics, power systems, power quality, renewable energy systems, electrical machines and drives, energy management and optimization, electric vehicles technology, transportation, smart-grid, smart-city, sustainability

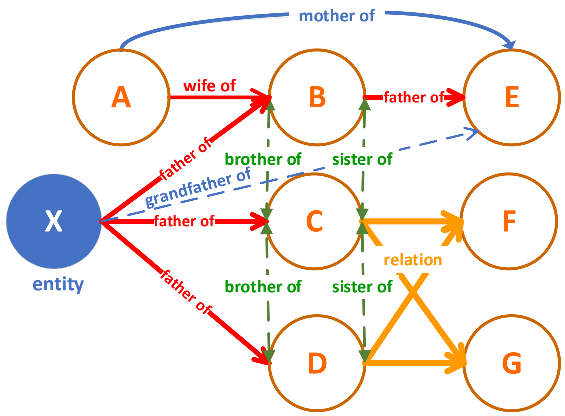
The section above is Section (a), starting at prompting the person who is answering to remember when she or he was a student, starting their university program, and the time they took to finish their first degree (probably a Bachelor's or similar degree), the questions asked were made in accordance to the next boxes. Then, the survey has a Section (b) enquiring about the motivations for young people to choose electrical engineering and electrification. The questions were:

5) In order to disseminate our profession with young people and children, some activities must be performed in order to motivate them. The following questions have been assumed to be good ones to center such activities. Do you agree with those, do you have comments, improvements, suggestions for new questions for allowing motivation for the young generation to take a path towards becoming Electrical Engineers and work with a Sustainable Electrification Paradigm?

- How is energy converted to power and electricity?
- How is energy transported and stored?
- How can energy be used efficiently?
- How do economics and policy govern energy technologies and vice versa?
- This would be an extra dialog box to write freely.

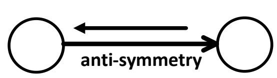
Part #2 of the survey was about capturing states and casual relationships, and mapping of courses and topics. The questions were:

6) This section of the Survey is a little bit complex, so we ask you for your patience and collaboration for a few more minutes of your valuable thoughts. The authors would like to make a graph, or a visual aid, that shows how a Curriculum and a Pathway for the future of education in Electrical Engineering should be. Please look at the image next, it defines a family in a graph-oriented way. Given an input X we can define the relationship of X to all other elements, you can see that it is depicted the example of an entity = father. Think on all the courses you wrote about today, and select a group of them, look at the picture below, and without the loss of generality and not being any gender-oriented, just imagine a Family of Courses, who in your family would be Parents (two parents) who would be children ? Can you Imagine another Family that would be in parallel and we would have Uncles, and Aunts, and Cousins, or you prefer to just describe one simple family of courses that you believe are important in your Best EE Curriculum for the 21st Century ?

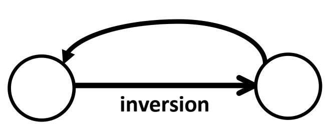


7) Given a course, there is another one that shows a symmetry in knowledge, although different subjects. Describe two courses to be an example like this graph.

8) Given a course, probably on the same path, there is another one that makes previous course stronger in a different perspective. Describe two courses as an example like this graph.

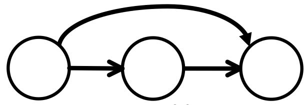


9) Given a course, you can flip another course, for example labs would support theory, problems would support essays, assembling would support design, and so on. Describe two courses to be an example like this graph.



10) This is a typical chain of courses: course 1 as pre-req feeding course 2 as a pre-req and feeding course 3, is it possible to bypass a typical course in a chain, and go directly from course 1 to course

3, removing any old course 2 ? Describe three courses as an example of a chain that you believe can be optimized.



composition

The last part was about asking inputs for a First (Gateway) and a Final (Capstone or Senior Design) course to wrap-up the whole curriculum, the narratives requested to the answerers were:

11) Suggest a "Gateway Course", suggest topics that could be taught for someone who just completed their Physics, Chemistry and Advanced Math to be Motivated with Electrical Engineering and Electrification in the 21st century?

12) Suggest a Capstone Course, typically capstone courses will involve all activities related to typical industrial management, project design, analysis, modeling, construction, presentation skills, social ethics. WHAT ELSE do you think should be developed for a student who just finished their core and electives and must understand how to Design Electrical Engineering and Electrification in the 21st century?

The authors started using some knowledge-mapping methodologies, there are apps such as Notion and Obsidian that can be used to connect ideas and concepts. There are families, as identified in the survey, a typical one is depicted in Figure 1, where starting from Calculus and Physics we can identify marriage with Chemistry and Materials Science, with offsprings of Electromagnetism, Electric Circuits and Energy Conversion, eventually supporting three foundation courses, or inner paths in electrification, namely Renewable Energy Systems, Power Electronics and Power Systems, the figure indicates three tags on *Philosophy*, *Physics* and *Mathematics*, such tags may help to connect to “other families in the curriculum pathways”; there are always short-cuts from a member of one family to another one.

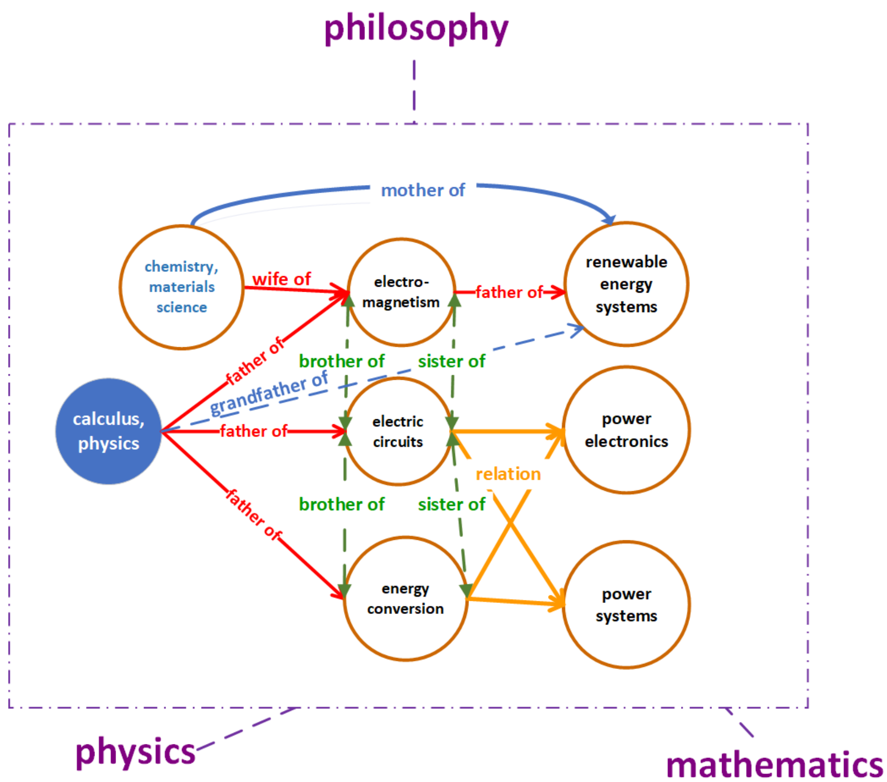


Figure 1 Family of courses in Electrical Power and Energy from foundation topics with intertwined relationships of courses aiming to specific formation in Electrification at the output.

The responses were rich. Figure 2 shows a *Word Cloud* based on counting the most cited words in each answer. The diagram simplifies the visual appeal of what is most important in that particular inquiry. For example, in the last section in identifying the Gateway at the top cloud as well as the Capstone course and the lower cloud, it is possible to see in the picture what is important to attract and motivate students to come to Electrical Engineering as regarding Electrification, and at the bottom what is important to make sure professionals just graduating from that program must master in their Senior Design experience.

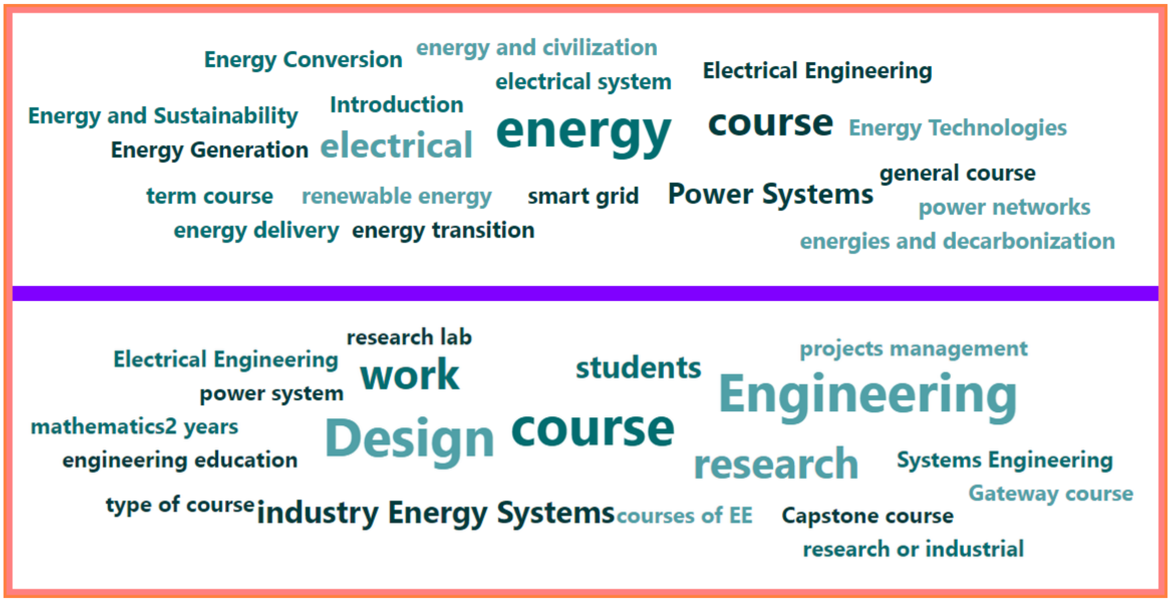


Figure 2 Written responses in surveys with word counting to identify visually the importance of meta-language required in the functional analysis of the narrative. The top word defines a Gateway Course, while the bottom words define a Capstone Senior Design Course.

3. Evolving Laboratory for Training in Electrification

Energy conversion from/to electricity is at the heart of electrification. Many traditional power programs keep physical labs with rotating machines, transformers, etc. More and more, those power labs disappeared. An example is the University of Florida (UF). In the 2000s, UF sent over the entire physical power lab to its sister college: the University of South Florida (USF). To date, the University of Illinois at Urbana-Champaign still has a physical lab-based lab course for undergraduate students. Yet, more and more schools go for digital simulation-based labs to teach electrification. In the CUSP program led by Ned Mohan of University of Minnesota, power system labs are completely software based, while the low-power, power electronics labs, are hardware based. For hardware experiments associated with rotating machines, toy-size machines have been used in Ned Mohan's lab kits to preserve the physical characteristics while reducing safety risks.

It is understandable that digital simulation labs are much easier to set up and free from worry about safety issues. Additionally, they are usually much less expensive to set up. With all the benefits, purely computer simulation-based labs have been suspected of not being able to offer students the same hands-on experiences as those from physical experiments. At MIT, Walter Lewin spent 60 hours preparing each experiment for the undergraduate physics classes. And the courses and their YouTube videos are extremely popular worldwide and showed people the fascinating beauty of physics visually. Indeed, at the beginning of the utilization of computer simulation, many well-known people were suspicious. According to Jerry Heydt, Eric T.B. Gross (1901-1988), a well-known professor in power who set up the power programs at Illinois Institute of Technology (IIT) and Rensselaer Polytechnic Institute (RPI), and a leader in the Power Engineering Society in the 1960s, was rather negative on computer analysis in power engineering.

It took decades to achieve accurate and reliable computer simulation. In power systems, the major work on power system dynamic modeling in the past decades was on perfecting synchronous machine dynamic models. Today, it is possible to replicate any results of an unbalanced induction machine obtained by hardware experiments in Gross' 1950 paper (The Goerges Phenomenon—

Induction Motors with Unbalanced Rotor Impedances) by computer simulation (see Kar et al. Circuit Analysis of Goerges Phenomenon in a Three-Phase Induction Machine. IEEE PESGM 2022). With the development of real-time digital simulators, demonstrations of electrical signals are now close to reality. In the recent IEEE Power & Energy General Meeting at Orlando, fascinating demos displaying electrical and communication signals were created by real-time digital simulators, e.g., RTDS. Real-time simulation also makes it possible to interconnect a simulator with a hardware device. Hence, after computer simulation, hardware-in-the-loop (HIL) experiments integrating real-time simulators and hardware devices have been adopted to set up labs. The main objective of the labs is for demonstration of theories. At its most fundamental level, several critical category theories on electrification are those associated with electro-mechanical energy conversion and electricity form conversion: power electronic converters convert electricity from dc to ac, from dc to dc, from ac to dc, ac transformers changes ac electricity voltage level. Indeed, those can all be demonstrated through computer simulation. Twenty years ago, in the early 2000s, it was still not feasible to rely on computer simulation to provide labs, since the computer power of a PC was low, and the simulation speed was too slow to be tolerated.

In the early 2000s, some schools adopted computer simulation programs based on phasors, e.g., PSS/E, PSLF. Those programs ignore electromagnetic transients and rely on phasors. The labs are good for demonstrating slow dynamics and are okay for graduate students. Yet these tools cannot demonstrate straightforwardly how a machine starts up, how a transformer is energized, and how an inverter works. It is with the advancements of both the computing power of a PC as well as the software simulation packages that the majority of the experiments at circuit/system level can be demonstrated and conducted in computer simulation today. Many software packages have excellent GUI design and provide a library of components. Thus, building a testbed in such an environment, e.g., RTDS, is a similar experience to walking into a physical lab and building a testbed. Students need to find a dc source, an IGBT inverter, and a load to build a simple system of a battery supplying a load. Students also need to put sensors in and get measurements. Inverter control can be further built to have measurements sent to controllers and generate reference signals. Finally, the reference signals are compared with high-frequency carrier signals to generate PWM pulses for IGBT gates. This testbed building procedure brings a similar experience to hardware testbed building. Only it is much faster, safer, and cheaper. In his talk at IEEE PESGM 2022, Jean Mahseredjian, the developer of EMTP-RV, said that EMT was “his religion”. Indeed, EMT or computer simulation in general can help conduct many types of analysis as a research tool and is also suitable for use for education in the electrical energy domain.

4. Impact of Artificial Intelligence

The term Artificial Intelligence was first used by John McCarthy in 1956, when he invited a group of lead researchers in advanced topics such as complexity theory, language simulation, neuron nets, abstraction of content from sensory inputs, relationship of randomness to creative thinking and learning machines to a summer workshop called the Dartmouth Summer Research Project.

In the past three decades, it is clear that fossil fuels with their environmental pollution and low efficiency impact the traditional and conventional power systems. These issues have been supporting a new paradigm of electricity generation locally at the distribution level, with renewable and alternative sources, making possible non-conventional distributed energy resources (DERs). Those are typically called microgrids (MGs), but there are other terms as well. The main idea is to have microgrids deployed on low- or medium- voltage active distribution networks. They can be advantageous in many different ways, such as improving the energy efficiency and reliability of the system, reducing transmission losses and network congestion, and integration of clean energies. Despite those clear advantages, challenges remain in implementing MGs with DER units. Those are related to power quality and stability issues, MG’s voltage and fault level changes, energy management, low inertia, further complex protection schemes, load and generation forecasting, cyber-attacks, and cyber security. For contemporary improvements in our total mix of energy resources and their conversion to electricity, it is also clear that Artificial Intelligence (AI) and Machine Learning (ML) are paramount for ushering in further advancements. In the timeline described in [1], several intertwined events have been pointed out. Three main types of AI and ML are based on (1) supervised learning, (2) unsupervised learning, and (3) reinforcement of learning. These techniques are used for different tasks such as regression, classification, clustering, and dimensionality reduction. Regression-based algorithms in which the output variable is a real or a continuous value were used in power system for network admittance, parameter and topology estimation, load forecasting, fault diagnosis, renewable power forecasting, load modeling, energy price forecasting, power flow modeling, and power system online sensitivity identification. Classification algorithms where the output variable is a discrete value were used for fault detection and classification, power quality disturbance classification, power system security assessment and classification, power system stability classification, and islanding classification. Among these algorithms, artificial neural networks (ANNs) and support vector machines (SVM), and decision trees have demonstrated robust and appropriate performance in classification problems. Deep learning is based on ANNs representation learning, which uses various layers for extracting different features from the raw input. Deep learning algorithms have been used for problems such as power system transient stability prediction, voltage instability prediction, load forecasting, and renewable power forecasting. Generative adversarial network (GAN) which was introduced in 2014, is a deep leaning model and one of the most promising methods for unsupervised learning in complex distributions. The GAN consists of two modules: the generative model (G) and the discriminative model (D). GAN techniques are used for power system dynamic security assessment with missing data, short-term scheduling of power systems, risk assessment, dynamic state estimation in power system, and phasor measurement unit data creation for improved event classification.

Traditional deep learning techniques are appropriate to extract the features of Euclidean data, whereas in different practical applications data are generated from non-Euclidean domains. To cope with this issue, researchers developed graph neural networks (GNNs). Graph is a kind of data structure, and the common graph structure consists of node and edge. The node contains entity information, while the edge contains relation information between entities. Graph neural networks are deep learning algorithms that can use the attributes of nodes and edges to improve the abilities to extract features. GNNs were used in power system studies for different applications. Some applications of GAN and GNNs as advanced AI techniques in power system studies are discussed in (E. Mohammadi, M. Alizadeh, M. Asgari Moghaddam, X. Wang and M. G. Simões, 2022). Reinforcement learning as a machine learning methodology was used for energy management, attack detection, load frequency control, power system resilience, power flow studies, and power system stability control. Clustering and dimensionality reduction techniques as unsupervised algorithms have been used for different problems such as predictive control of power plants, electricity customer classification, pattern recognition of load curves, reliability modeling of power plants, power quality assessment, power system capacity expansion modeling, electricity price forecasting, and load profiling.

There are so many challenges to still implement related to electrification and AI-based techniques in microgrids, such as energy management, load and generation forecasting, protection, power electronics control, and cyber security. Different AI tasks, such as regression and classification in microgrids, are discussed using methods including machine learning, artificial neural networks, generative adversarial networks, graph neural networks, fuzzy logic, support vector machines, etc. As an example of application of AI, in the design of a small-scale wind farm, integrated into a microgrid for intelligent monitoring and protection is discussed. Finally, the advantages, limitations, and future trends of AI applications in microgrids are given.

With such a recent widespread waking up of AI, particularly in large language modeling in our society, which professions will become obsolete in the near future? What skills are needed in a world where AI is used? How should AI be incorporated into the curriculum? Will AI change teaching as we know it? Can AI assess students fairly? Can AI reduce the impact of dyslexia, dyscalculia or other learning difficulties? Answers to these relevant and complex questions are directly related to the use of AI in education. In Engineering, AI has the potential to revolutionize all kinds of fields and, in particular, energy efficiency and operation of electric grids, where it can optimize energy consumption, analyze the data from the energy grid, and predict where the grid needs maintenance or reinforcements, which are the best places to install new power plants, and so on.

As for engineering education, the new educational tools are already incorporating AI with promises to revolutionize both the teaching and learning process. Recently, the authors carried out a worldwide survey which showed that ChatGPT is becoming the AI tool of preference among engineering faculty and students as depicted in Figure 3. One of the most concerning dangers of AI is algorithm bias that can be programmed with features that influence people and increase discrimination and unfairness. The consequences of biased algorithms can be severe, deepening societal division, discrimination, and hindering social progress.

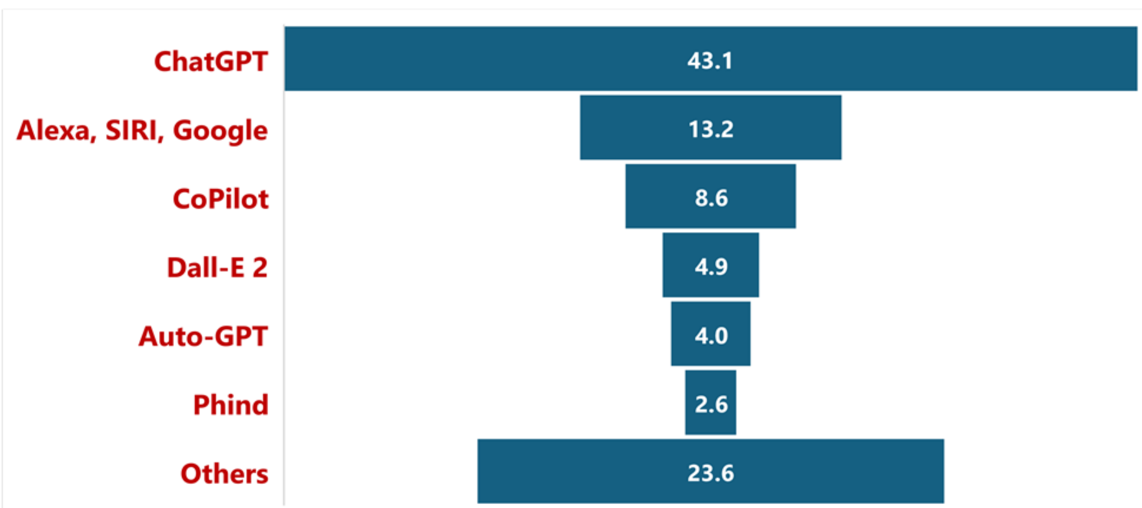


Figure 3 Survey on Generative AI LLM Tools Ranked by Their Adoption

Technology is rapidly transforming the way we use and convey information. Although it offers great benefits and continues to evolve, it is important to consider the ethical implications of the developments. AI is one of the transformative technologies that has a significant potential, but it comes with its own set of operational and ethical issues. Technologies such as facial recognition, etc., has the possibility of being misused. Another ethical issue is the concern of bias as algorithms are based on training data that have a human prejudice, and consequently laden by the values of the creators' algorithms.

The IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems has approved the IEEE P7000™ standards series under development which cover topics from data collection to privacy, to algorithmic bias and beyond. Let us hope this initiative may take away much of the non-sense and hype of AI applications to avoid major problems in the future

5. A Framework for a Curriculum

Electrical Engineering as a field can be evaluated at many levels of abstraction, for example, as portrayed in Figure 4. Then, inside such a myriad of possibilities, it is possible to aggregate and construct how groups of courses can be connected to each other, similarly to a "family", for example, to a family of courses in renewable energy systems, power electronics, and power systems, are descendent of electromagnetism, electric circuits, and energy conversion, which, in turn also are from mainstream foundation subjects of chemistry, materials science, calculus, and physics.

There is always a boundary layer that will hold these as a collection, as a set, with properties that would be tagged to scientific and analytical, such as the lines connecting to Physics, Mathematics, and Philosophy as foundations. Similarly to a house that has a concrete foundation, with framed structures where the weight of the floors and walls is supported by vertical studs, which are connected to horizontal members called joists, we are supposed to construct such a rigid frame, that makes coherence and consistency for all possible pathways and knowledge approaches in a modern curriculum. Therefore, some of the curriculum structures that we find in the past should be kept, while given the requirements of our contemporary society we need to find the tagging points to connect a new curriculum.

In order to establish a coherent curriculum for the future, it is necessary to concentrate on some fundamental components as described below, by the following aspects. For example, for electrical energy systems, the pathways indicated in Figure 10 capture a possible implementation of several families of interconnected sub-areas, showing eventually an emerging core. The different parties play a fundamental role and have their specific interests and responsibilities, with specific disciplines and approaches as portrayed in the knowledge boxes.

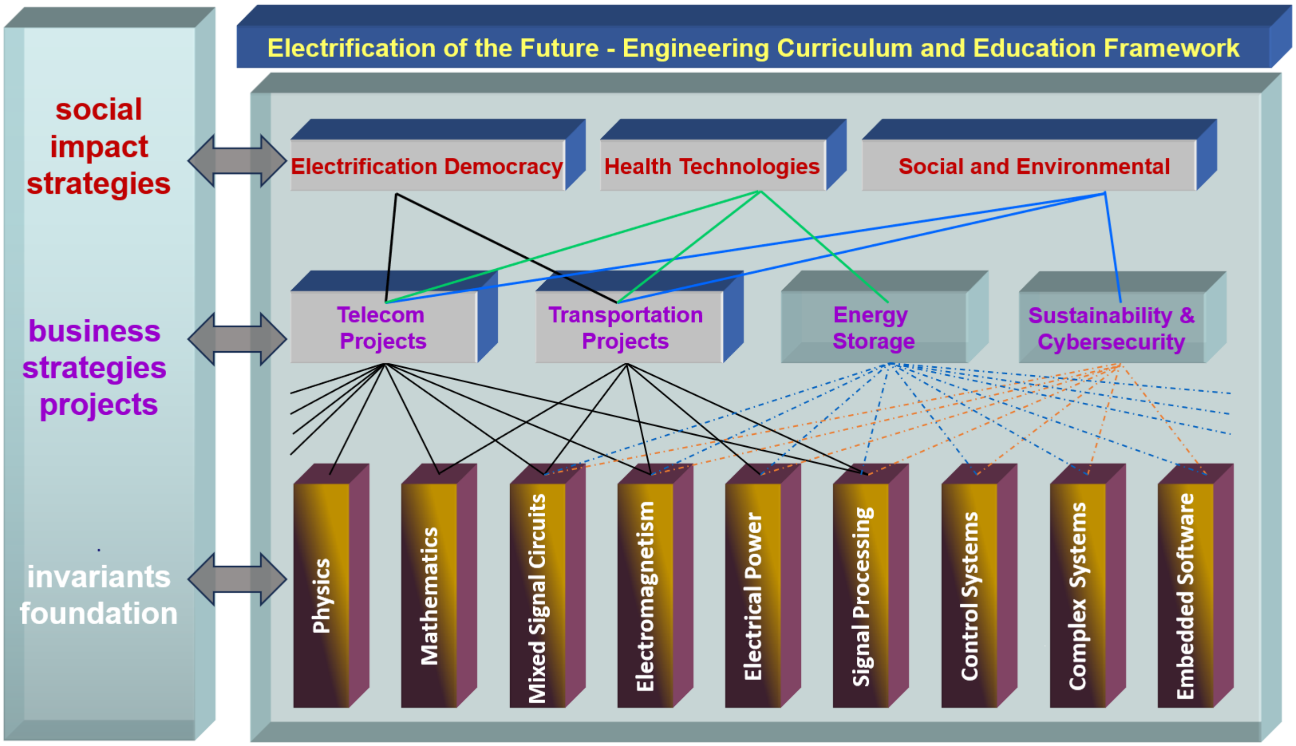


Figure 4 Pathway of sub-areas and interconnected courses with overreaching outcomes.

The disciplines within each aspect define the technical content.

1. **Physical Aspects**
    a. Energy generation, transportation and management
    b. Physical laws, system performance
    c. Instabilities compromise performance/security

2. **Life Sustaining Aspects**
    a. Environmental dimensions and impact

3. **Control Aspects**
    a. Power over individual components / whole system
    b. Distributed/delegated to intelligent systems

4. **Social and Economic Aspects**
    a. System and generated electricity have economic value
    b. The breakdown can cause enormous financial losses

5. **Juridical and political aspects**
    a. Generation and trading are covered by juridical contracts.

6. **Moral aspects of Electrification**
    a. We cannot live without electrical energy.
    b. The obligation of stakeholders to supply energy continuously.

Concerning stakeholders (government, local authorities, energy suppliers, energy transporters), customers (industrial, commercial, residential), action groups, their interests need to be considered and focused on specific areas.

- **Government and Local Authorities**
  Focus on the juridical aspect of electricity systems.

- **Customers**
  Focus on the economic, security and environmental aspects of energy.

- **Action Groups**
  Focus on the environmental dimension of energy production and transportation.

6. Philosophy of Technology, Education, and Teaching Methods

Why is Philosophy important for Electrical Engineering? The philosopher Wilfrid Sellars characterized the aim of philosophy as the effort “to understand how things in the broadest possible sense of the term hang together in the broadest possible sense of the term.” (Sellars 1962). And that is one of the reasons the authors of this paper are convinced that Philosophy is of paramount importance for understanding the function and engineering education. In the middle of the AI revolution, the Philosophy of Technology, as a sub-field of philosophy that studies the nature of technology and its social impacts, becomes extremely important.

The Functions of the Philosophy of Technology are analytical, critical, and directional. These functions serve as a guide for the learning and application of all disciplines. This could be one course or distributed among different disciplines. There are several philosophies and teaching methods, including:

- Project-Based Learning which emphasizes hands-on learning and solving real-world problems through projects, which can involve collaboration with other students or professionals.
- Experiential Learning which focuses on learning through experience, which can include internships, co-op programs, and service-learning projects.
- Interdisciplinary Learning which emphasizes the importance of integrating knowledge and skills from multiple disciplines to solve complex engineering problems.
- Design Thinking which emphasizes empathy, creativity, and iterative problem-solving to develop innovative solutions.
- Ethics and Social Responsibility which emphasizes the importance of considering ethical and social implications of engineering projects and the preparation of engineers to take responsibility for the impact of their work on society.
- Lifelong Learning which emphasizes the importance of continuous learning and professional development throughout an engineer's career.

It is important for a well-rounded education to include not only the technical skills required for scientific and engineering careers, but also the humanities, social sciences, and arts. This interdisciplinary approach is designed to help students develop critical thinking skills, creativity, and the ability to work collaboratively across diverse fields.

Furthermore, the electrical infrastructure of the future will be much more complex than the current one. It will have to integrate traditional and sustainable energy sources, current and new distribution systems, customers with very different consumption patterns, and intelligent control systems. However, at the moment, there are no sufficiently comprehensive engineering models that can deal with the higher level of complexity of future electrical networks.

7. Leaders who Most Impacted the Electrification Sector in the Last 50 Years

The authors also conducted a worldwide survey on the text/authors who most impacted the education and practice of electrical engineering in the last several decades. The results are presented below in Figure 5. These books are considered to be the most valuable formative and conceptual texts to support "invariants and foundations" in any EE curriculum, especially when aligned with Electrification. They are listed in section 'Book Recommendations' as well as in Probe Further'.

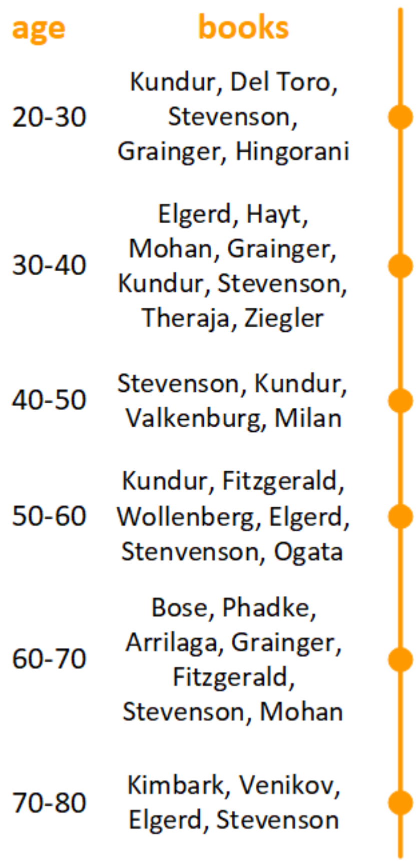


Figure 5 Books/Authors who most contributed to the EE education in the last 50 years.

8. Distance Learning - Then and Now

Distance Learning in the past was based on recording lectures with a camcorder, making a VCR to be sent via post services, or pick-up by the student at the school. There were also some universities and institutes with correspondence courses, mostly on labor skills. During the first few years of the 21st century distance learning became more and further professionalized, sometimes universities would have contracts with centers and foundations to take care of regular credits, as well as lifelong learning activities, and certificates. Distance learning in electrical engineering, like any other discipline, presents both opportunities and challenges. Below is an overview of some key aspects: (I) distance learning allows students to study at their own pace and on their own schedule, (II) the time flexibility is especially beneficial for individuals who may be working or have other commitments. Other positive aspects include access to resources and online platforms, including lectures, simulations, and virtual laboratories, enhancing the learning experience. (III) the set up also allows for students to enroll in programs offered by institutions around the world, giving them access to a diverse range of expertise and perspectives, and (IV) distance learning can also be cost-effective for both students and institutions in some aspects of the learning process. The cost reduction of relocation and travel is also considerable. In addition, it seems that Distance Learning helps the inclusiveness of historically displaced people in higher learning educational opportunities.

Online platforms can influence adaptive learning technologies to improve the educational experience of individual students, addressing their strengths and weaknesses. Alternatively, the lack of hands-on experience is a real problem in electrical engineering as it often involves hands-on work in labs.

Ensuring the integrity of evaluations in an online environment can also be challenging. Institutions need to implement effective strategies to prevent cheating and plagiarism. Also, the lack of face-to-face interaction with professors and peers can result in a shortage of immediate feedback and a potentially less engaging learning involvement. While electrical engineering distance learning provides flexibility and access to a broader range of resources, it also creates challenges related to hands-on training, networking, technical issues, and maintaining student engagement.

Stanford University offers individual online courses covering a wide array of subjects, including computer science and engineering. These courses are often accessible to learners around the world. They also offer Online Certificates in collaboration with various departments. Some departments offer fully online graduate degree programs, allowing students to earn a master's degree through distance learning. However, the availability of online graduate degrees may vary by department. The Massachusetts Institute of Technology (MIT) offers a variety of online courses and resources through its MIT Open Courseware (OCW) initiative. MIT OCW provides free access to a vast range of course materials, including lecture notes, assignments, and exams. However, it's important to note that OCW doesn't typically grant degrees. Successful distance learning programs often incorporate a combination of online resources, virtual labs, and opportunities for real-world application to address these challenges. Only a small percentage of the EE program should be allowed to utilize DL in the overall structure. Distance learning has been an evolving trend in education, including engineering, and its future is likely to be influenced by various factors such as technological advancements, virtual labs and simulations, virtual reality, flexible scheduling, industry collaboration, personalized learning paths, and interdisciplinary approaches. Each institution needs to carefully evaluate the use of Distance Learning, particularly for programs like Electrical Engineering, which requires a substantial amount of hands-on and lab work.

Is there a place for DL in EE education? Yes, definitely, but much care needs to accompany the implementation of the programs. After COVID-19, a whole new paradigm of online, remote, trainings, and teachings were introduced. There have been several sites hosting such services, some academic in nature, others informational, or alternatively, specifically skilled people will sell their knowledge independently. Starting to generate online material is learning about creating and editing web pages, with interactivity, and assessments. A MOOC became a de-facto distribution of course materials, such as Blackboard, Canvas, and Moodle, even for face-to-face courses. Then, the obligatory attendance of physical classes, taking attendance, or signing lists of presence became a thing of the past , and teachers, instructors, and professors now have to learn how to deal with low attendance and high maintenance people who are only logged in and never show up to class. However, providing students with timely, frequent, and relevant feedback on assessed work to guide their study efforts can be asynchronous. Eventually, a large number of off-campus students may benefit, democratizing education and aiding in the social mobility of individuals previously excluded. This could represent another paradigm that must continue to evolve in the education of 21st-century electrical engineers in electrification.

9. Towards a Holistic Perspective

In order to integrate multi-disciplinary engineering projects, two additional disciplines may be useful: Systems Engineering and Engineering Systems. Figure 6 shows an example of approaching the integration of a PV system into the electrification of the life-sustaining infrastructure of an electric grid. Engineering Design Norms should consider the following: Cultural Suitability, Environmental Awareness, Stewardship, Justice, Caring, Trust, Transparency, Integrity, Responsibility, and Humility (related to the limitations of engineering).

The trouble is that we need to continue using traditional models to design the next generation of electrical infrastructures, or important interactions between technical systems will be ignored; non-technical dimensions, such as the social behavior of customers or the moral dimensions of intelligent control systems, will be ignored; and economically weak interests neglected.

Aspect	Engineering Systems	System Engineering
Scope	**Electrification of Power systems**, smart energy system	**PV generation system, isolated** microgrid system, substation
Focus	**Philosophy of technology**, design criteria, impact on human life	**Focus on technology, equipment, controllers**, applications
Policy	Use of solutions to adapt to the advances of electric power systems in society	Use of standards, methodology, requirements
Socio-technical	Crucial for smart grid projects to present a holistic and empowering vision for society as a whole	Important for smart grids to work properly, matching quality and reliability
Stakeholders	Focus on the environment, underprivileged by modern technologies, researchers	Focus on consumers, “prosumers”, energy agencies, professionals
Roles	Grids architecture, energy markets, project design, social aspects from smart grids, politics, biology, and others	Construction of new environments, smart grid performance, electrical engineering, information and communication

Figure 6 Systems Engineering (SE) and Engineering Systems (ES) for electrification integration.

The authors maintain an open-source repository with the data collected and analyzed for this paper. Readers are encouraged to visit, re-use, and contribute to further analysis that may enrich the educational purposes of this work. The URL is https://github.com/mgodoysi/electrification-education-21stcentury

10. Conclusion

In this paper, a comprehensive discussion on the past developments of electrical engineering, with a research structure based on surveys collected from professors, students, professionals and engineers, supported a vision of curriculum implementation for the future of electrical engineering. Noting in particular, that Electrification requires consideration of emerging technologies, interdisciplinary approaches, and a focus on both technical skills and broader competencies. A balanced curriculum should include strong fundamentals in mathematics, physics, and core electrical engineering concepts.

Furthermore, interdisciplinary integration that connects electrical engineering with fields like computer science, materials science, biomedical engineering, and environmental science should be part of the program. There must be emphasis on the intersection of electrical engineering with emerging technologies such as quantum computing, artificial intelligence, and the Internet of Things (IoT), as well as not underestimating the importance of hands-on learning experience through labs, projects, internships, real-world projects industry scenarios, encouraging students to apply theoretical knowledge to practical problem-solving. Programming skills, covering languages relevant to electrical engineering such as Python, C, etc., should not be minimized.

Courses on engineering ethics, responsible innovation, and sustainability to instill a sense of social responsibility, and research opportunities for undergraduate students to encourage the exploration of cutting-edge technologies and contribute to advancements in the field should also be part of the curriculum. A citizen of the world, with preparation to be a leader in Electrification, will also need courses that provide a global perspective on electrical engineering within the sustainability framework and should be included in Capstone Projects.

The authors are very much aware of the challenges of the issues related to how electrification should continue to have a positive impact in society as a critical life sustaining infrastructure. The authors are also mindful of the risks in predicting anything for the future. We hope that the proposed framework and curriculum will give a sound direction with due flexibility in the face of the technical developments, culture, and individual temperament and gifts of individual students, so that they will be able to flourish and not be hindered by our suggestions. Prof. Lewis, from Oxford, expressed this tension very well when he said:

"That is the point. While we are planning the education of the future, we can be rid of the illusion that we shall ever replace destiny. Make the plans as good as you can, of course. But be sure that the deep and final effect on every single student will be something you never envisaged and will spring from little free movements in your system which neither your blueprint nor your working model gave any hint of."[My First School, CSL, 1943].

11. Book Recommendations

The references and bibliography below are consistent with our approaches, and recommendation for a balanced curriculum, they have been selected with their historical impact in the past 50 years with a few other recommendations for the reader to probe further.

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To Probe Further

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