Making our Electric Power Grids Sustainable

by Ute Ebert and Jannis Teunissen (CWI)

Electric power grids will play a key role to transport energy in a sustainable way. However the switches in present high voltage grids operate on SF_6 gas, which is the worst greenhouse gas known. To investigate alternative gases, CWI (the national research institute for mathematics and computer science in the Netherlands) and Eindhoven University of Technology (TU/e) now start their third project with Hitachi Energy as the main industrial partner. While TU/e performs experiments, CWI simulates the pre-spark phenomena in these gases. These discharges are surprisingly different from discharges in air and pose new numerical challenges.

Energy transmission by electric power grids plays a dominant role in the transition to a sustainable energy supply. It is foreseen that by 2050, electricity production will double and two-thirds of this electricity will be delivered by renewable energy sources, leading to massive changes and investments in electric grids. To interrupt an electric current in these grids (in particular, in high-voltage transmission lines across countries) one cannot simply separate two electrodes like in a light switch, because an energetic and destructive electric discharge would then form in the gas between the electrodes. Specialised switchgear is therefore required, in which these discharges extinguish in a controlled manner.

Today's switchgear uses gaseous SF_6, which has favourable properties for current interruption. However, SF_6 is also the most potent greenhouse gas. Its global warming potential is 23,500 times that of CO_2 on a 100 years' horizon, but its residence time in the atmosphere is estimated as 800 to 3,200 years by different authors, which further increases its climate impact [L1]. In 2006, the European Union therefore has banned the use of SF_6 in all application fields – except in high-voltage switchgear, because no alternative was available. However, legislation in the US and in the EU [L2] now requires industry to replace SF_6 with alternative gases with significantly lower global warming potential as soon as technically possible.

Alternatives for SF_6 gas have been identified in recent years, but now the behaviour of electric discharges in these gases needs to be better understood, as one cannot simply replace one gas by the other in existing equipment. Researchers at CWI and at TU/e now start their third project on studying discharges in relevant gases, funded substantially by the Dutch national research funding agency, NWO, and with matching by Hitachi Energy (previously part of ABB Corporate Research, Baden Switzerland). While the Eindhoven team performs experiments, the CWI team develops computational methods and analytical approximations for electric gas discharges in general, and for air and for the new gases specifically.

Simulating the growth of electric discharges is computationally challenging. Electron processes take place on micrometre and picosecond scales, while a full discharge develops on scales three to six orders of magnitude larger. We therefore have developed computational techniques such as adaptive mesh refinement and parallelisation for dynamic 3D simulations. To describe the evolution of the species in a discharge, so-called drift-diffusion-reaction models are commonly used. They are coupled to the Poisson equation for the electric field. The reaction and drift terms strongly depend on the changing electric field, which leads to highly non-linear growth and the formation of elongated "streamer" channels in air (see Figure 1).

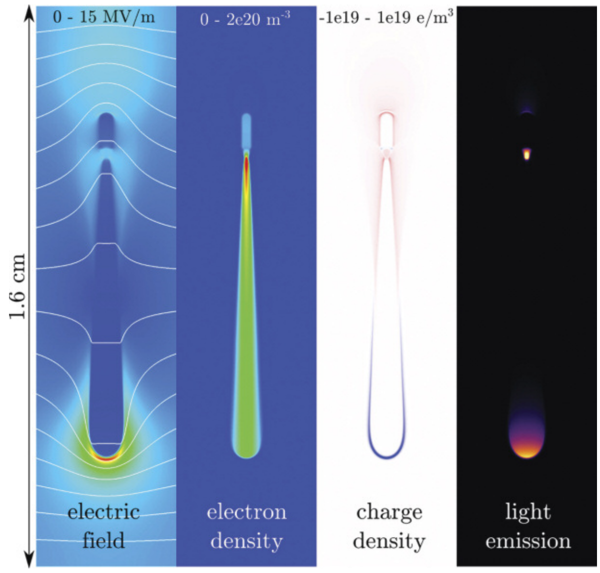

Figure 1: Positive streamer in air. The discharge growth results from the electric field enhancement at the head of the growing channel (source: [3]) .

We have recently made important progress towards the validation of discharge models by comparing the propagation [1] and branching [2] of simulated streamer discharges in air with dedi-

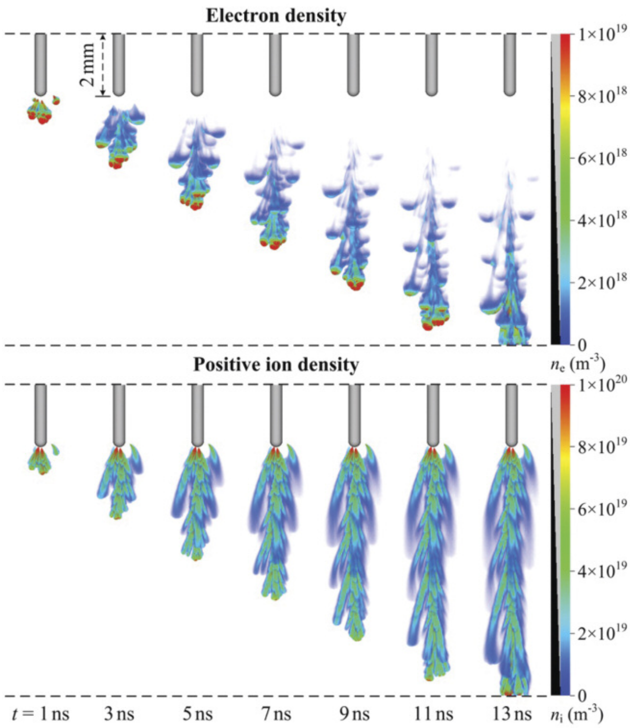

Figure 2: Negative streamers in a new insulating gas. Source: https://arxiv.org/pdf/2308.08901.pdf.

cated experiments by the partners in Eindhoven. However, the new gases pose new physical and computational challenges.

First, positive discharges in air develop rather smoothly (see Figure 1) due to a process called photoionisation, but photoionisation will likely be much weaker or negligible in the new gases. This will lead to highly stochastic discharge growth that cannot be described with drift-diffusion-reaction models, but instead requires computationally more expensive particle models [3].

Second, the lifetime of free electrons in the new gases is extremely short, typically much less than a nanosecond, because they rapidly attach to gas molecules. This means that a much higher voltage has to be applied before a discharge can start, and that the resulting electric fields can be much higher. Another effect is that the conducting channel behind a discharge rapidly disappears, as visible for negative discharges in one of the new gases in Figure 2.

Third, electric discharges cause gas heating, which in turn affects both gas and discharge properties. This process has to be understood in the new gases, but it takes place on significantly longer timescales than are usually considered in streamer discharge simulations.

From a modelling point of view, there are thus several challenges that need to be addressed. The range of models and methods that have been developed for discharges in air [3] – particle and fluid models, adaptive mesh refinement, adaptive particle management, model reduction, etc. – needs to be extended so that streamer phenomena, evolution on longer timescales and gas-heating effects can be understood in the new gases.

Within the new project, we will continue to develop and use both gas-specific models and general methods of gas discharge physics (that are also applicable to lightning physics and other application fields). Together with our experimental colleagues, Sander Nijdam and Tom Huiskamp in Eindhoven, we aim to contribute to making our electric energy supply even more sustainable, and in parallel to develop more fundamental knowledge on electric gas discharges.

Links:
[L1] https://tinyurl.com/mszeum2h
[L2] https://tinyurl.com/46843jh5

References:
[1] X. Li, et al., "Comparing simulations and experiments of positive streamers in air: steps toward model validation", Plasma Sources Sci. Technol., vol. 30, no. 095002, 2021.
[2] Z. Wang, et al., "Quantitative prediction of streamer discharge branching in air", Plasma Sources Sci. Technol., vol. 32, no. 085007, 2023.
[3] S. Nijdam, J. Teunissen, and U. Ebert, "The physics of streamer discharge phenomena – a topical review", Plasma Sources Sci. Technol., vol. 29, no. 103001, 2020. https://iopscience.iop.org/article/10.1088/1361-6595/abaa05.

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Sustainable Scheduling of Operations: Advancing Self-Consumption through an IoT Data Framework

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Due to the global energy crisis and increasing CO2 emissions, energy efficiency has become a crucial focus. This has led to an increased usage of solar photovoltaic power generation in residential buildings to meet climate and energy targets set by the "Paris Agreement". With the growing number of Internet of Things (IoT) devices, implementing an intelligent home energy management system can offer energy and peak demand savings. However, planning the optimisation of these devices faces challenges due to the user-defined preference rules, and convergence issues arise when managing multiple IoT devices. We have devised a novel IoT data management system, called GreenCap, which uses a Green Planning evolutionary algorithm. The system focuses on load shifting of IoT-enabled devices, considering factors such as integrating renewable energy sources, managing multiple constraints, peak-demand times, and dynamic pricing. We have implemented a complete prototype of the GreenCap system on Raspberry Pi, connected with the openHAB framework, able to generate sustainable plans ensuring a high level of user comfort and self-consumption, while significantly reducing the imported energy from the grid and CO2 emissions.

Residential loads constitute a substantial portion of the overall demand placed on utility grids, with this figure steadily expanding in tandem with the increasing proliferation of various associated applications. The global count of IoT-connected devices is anticipated to reach 30.9 billion units by the year 2025, and is further projected to soar to 100 billion connected devices by 2030 [2]. The global market for home energy management systems (HEMS) has witnessed substantial growth, expanding from US$864.2 million in 2015 to US$3.15 billion by the year 2022 [3]. The Paris Agreement solemnly signed in New York City on April 22th 2016, falls under the United Nations Framework Convention on Climate Change and encompasses the areas of greenhouse gas emissions mitigation, adaptation, and finance. There has been a significant escalation of approximately 140% in the financial repercussions associated with power generation pollution in the year 2021.

Green Planning encompasses computational methodologies that strive to expedite sustainable advancements by implementing load-shifting strategies that address peak-demand reduction. This approach is distinguished by its long-term perspective, intending to supplant conventional environmental protection methods by incorporating economic realities while preserving ecological values and natural resources. An essential catalyst for managing energy consumption and mitigating CO2 emissions lies in the widespread adoption of the IoT infrastructure. This interconnected network facilitates seamless