Coastal Electrification Using Hydrogen Technology and Distribution Grid Flexibility Potential

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Abstract

This paper aims to analyze the impact of electrifying a coastal fishing fleet on the distribution network. The objective is to address a production and capacity planning challenge by optimizing hydrogen production over the system's lifetime, while also exploring the possibility of utilizing the hydrogen storage to enhance system flexibility. The scope includes: scenarios to assess how the electrification of the coastal fishing fleet affects the distribution network, and conducting simulations to investigate the load flow problem connecting a water electrolyser to the grid. The study will also examine the potential for flexibility in the Lofoten area, utilizing the electrolyser for flexibility purposes from a DSO perspective.

Key words - distribution grid, hydrogen, flexibility

I. Introduction

In order to achieve a fully renewable power grid, it is necessary to combine large-scale renewable power plants with the use of primary Renewable Energy Sources (RES) as small-scale distributed generation (DG) [1]. Norway, a country with a lengthy coastline and abundant resources, has a rich history of seafood exportation. However, the majority of Norwegian fishing boats currently use diesel propulsion systems, resulting in fishing vessels contributing approximately 2% of Norway's annual emissions, or 878,000 tons of CO2, in 2020 [2].

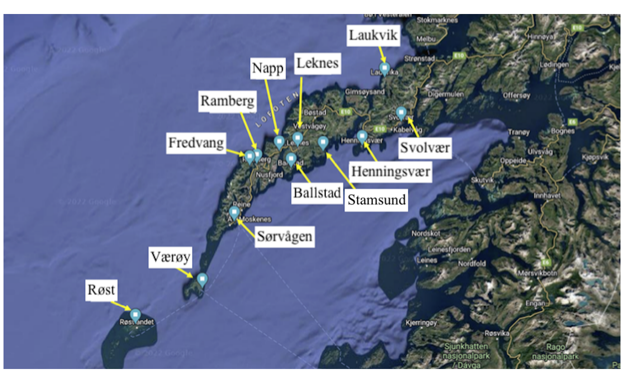

Figure 1: Location of the fishing fleets in Lofoten taken from Zerokyst project.

The study is a part of the project [1] aiming to decarbonize the seafood industry, electrify and demonstrate optimal energy solutions in Lofoten. The project includes developing a zero-emission driveline, a new fishing vessel, and preparing 10 vessels for conversion, along with conversion and maintenance services and a complete solution for flexible electricity and green hydrogen supply. It will help to reduce emissions from fishing and aquaculture vessels by 50% by 2030, potentially generating values of 100 million NOK [2]. The paper is organized as follows: Chapter 2 discusses the changing power system in response to the global climate crisis, while Chapter 3 is focused on the theory behind hydrogen technology as a potential solution. Chapter 4 presents the methodology for the network modelling and the model of the electrolyser. The main results of the study are emphasized in Chapter 5. Finally, the main conclusions of the study are summarized in Chapter 6.

II. Power System in Change

The power system is in need of a change, as the traditional centralized model based on large-scale power plants and transmission lines is no longer sustainable in the face of climate change, market and rapid technological advancements [3]. One of the key challenges that the future power system must address is grid stability, particularly in the context of increasing penetration of RES and distributed energy resources (DER). To achieve this, the future power system is likely to be characterized by a more decentralized architecture, with a greater emphasis on the use of distributed energy resources like solar panels, wind turbines, and battery storage systems [1]. These RES will play a critical role in balancing variable loads in the distribution network and ensuring that voltage quality is maintained, even as the system experiences fluctuations in power supply and demand [3].

Ultimately, the success of the future power system will depend on the ability of industry stakeholders, grid operators, regulators, and policymakers to work together to design and implement a more resilient and sustainable energy infrastructure that is capable of meeting the needs of a rapidly evolving world.

Hydrogen technology is emerging as a promising energy storage and flexibility solution, particularly in the context of

[1] ZeroKyst. Flexible and competitive hydrogen supply. 2022. URL: https://zerokyst.no/

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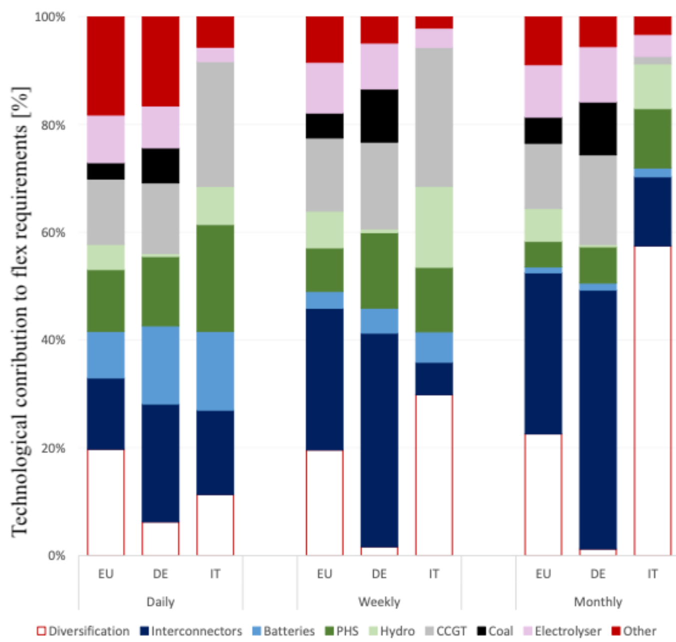

Figure 2: Contribution to flexibility requirements [4].

the growing shift towards RES as can be seen from Figure2. With the ability to be produced using renewable electricity and water, hydrogen can be used to store excess energy during times of high production and then be used as a fuel or feedstock for various industrial processes when demand increases [3]. Green hydrogen, which is produced through the electrolysis of water using RES, is particularly appealing as it offers a sustainable and carbon-free alternative to traditional fossil fuels [5].

However, electrolysers also introduce a new variable load in the distribution network, as their energy demand can be varied based on electricity consumption [6]. To manage this variable load, smart grid technologies and energy management systems are needed to ensure that the electricity supply and demand are balanced in a stable and sustainable manner [7].

III. Hydrogen technology

The use of hydrogen as an energy storage and carrier, particularly through the production of green hydrogen using electrolysers, represents a promising avenue for achieving a more sustainable and resilient energy system. However, this will require careful management and coordination of the energy network to ensure that the distribution network is able to accommodate the variable load introduced by electrolysers.

A. *Electrolyser*

The EU Hydrogen Strategy aims to decarbonize hydrogen production and increase its use in industries that use a lot of energy, setting targets of 6 GW and 40 GW of renewable hydrogen electrolysers by 2024 and 2030 [8]. Norway has expertise in the hydrogen value chain, including electrolysers, and aims to produce green hydrogen to satisfy emission reduction requirements. The maritime industry will see a 7% increase in hydrogen consumption by 2030, and there is a pressing need to drastically reduce emissions [2]. However, the introduction of hydrogen-electric vessels is fraught with technical and economic difficulties, and the rules for using them as fuel will take some time to establish [9]. Hydrogen production cost is still considerably higher than low-carbon and fossil-based hydrogen produced from natural gas due to the cost of renewable power and the initial capital expenditure.It was noted that hydrogen storage has a high energy density, making it a good option for storing large amounts of energy in small spaces [10]. Hydrogen storage systems also have high energy storage performance and can contribute to voltage and frequency stabilization. In EU, hydrogen is expected to play a crucial role in reducing greenhouse gas emissions and can also serve as a flexibility provider in the energy market as can be seen from Figure 2.

Water electrolysis is the process of using electric power to generate synthetic H2. Alkaline and proton exchange membrane (PEM) electrolysis are two low-temperature technologies used for power-to-H2 conversion [11]. Alkaline electrolysers are well-established, have high long-term stability, and can produce hydrogen at a high rate, but have a small partial load range and slow dynamic response times. PEM electrolysers have higher power densities and efficiency, a good partial load range, and quicker dynamic response times, making them suitable for hydrogen production pathways based on wind turbines [11]. PEM electrolysers have the interesting capability of fast dynamics in the electrolysis process, allowing for adjustments to the amount of electricity used in less than one second [6]. This opens up potential demand-side response schemes to assist the operation of electrical power systems. A complete representation of a PEM electrolyser unit includes the power conversion system, modelling of the stack, and balance of the plant [6]. The efficiency of a PEM electrolyser is limited by various factors, including overvoltages, parasitic currents, and inefficiencies in the stack and system design [12]. The lifetime of a PEM electrolyser is affected by factors such as the quality of materials, operating conditions, and level of maintenance [13]. An electrolyser can function in three different states: production state, hot-standby state, and idle state, and parameters from each state need to be considered for the system to function as a flexible resource.

B. *Flexibility possibilities in Lofoten*

When modelling of PEM electrolysers as a flexible resource in a distribution grid one of the challenges is finding the best combination of meeting hourly demand through production, storage withdrawals, or a combination of both. Hydrogen production and storage capacities are important parameters to investigate, and it is desired to find the optimal capacities that yield a higher value than estimated hydrogen consumption. Different decision variables for modelling the water electrolyer includes capacity, production quantity, and storage quantity, as well as operational variables to track the state of the electrolyser equipment. The EU's "Fuel Cells and Hydrogen 2 Joint Undertaking" (FCH 2 JU) has established reliable techno-economic values and targets for developing PEM and alkaline electrolysis technologies, regularly updated and involving public and private industry stakeholders [14]. [14] presents parameters for modeling these systems based on EU studies and ongoing projects. Key parameters include system and stack lifetimes, water consumption, efficiency, and input power. [16] also presents a techno-economic model for PEM electrolysis, including technical and economic parameters. Relevant parameters for technical and economical paramenters found from [15], [14], and [12] can be found in Table I. Based on a literature review, relevant parameters for a electrolyser as a distribution generation in the power system are also presented in Table I.

Table I: Overview of the parameters for modelling.

Technical and economical parameters	**Parameters affecting grid parameters**
Hydrogen production rate	Minimum partial load (safe load of the electrolyser)
Nominal voltage	Power demand (maximum)
Nominal current	System efficiency
Operating temperature	Response time
Hydrogen pressure	Standby consumption
Oxygen pressure	Lifetime stack
Current density	Max number of cold starts
	Min response time (from hot standby to full load or vica versa)

Water electrolyser has the possibility to contribute as a flexible resource for the distribution network grid. Here we refer to flexibility as the ability to operate the water electrolyser plant at different power levels [16]. Water electrolysers can produce hydrogen during off-peak hours to be used during peak hours, acting as a flexible resource for load shifting and storage. Additionally, electrolysers can provide dynamic responses that can support demand response, local voltage support, and frequency support. Electrolysis also generates excess heat that can be utilized for waste heat recovery, increasing system effectiveness and supporting a green hydrogen economy. Finally, hydrogen production and storage has the possibility of developing a flexibility market in Lofoten area where end-users can become a prosumers and provide flexibility by managing loads, and allowing the DSO to request and activate the needed flexibility. As well as it could be extended to DSO-TSO coordination and participation in the system services provision.

IV. Network Modelling: case study

This study aims to investigate the potential effects of electrifying a coastal fishing fleet on the distribution network in the Lofoten. To achieve this, a network model of the distribution network is created using the PowerFactory DIgSILENT, which is commonly used for power system analysis. The study also explores various scenarios related to integrating electrolysers into the network.

A. Network model

The network in the Lofoten area is a medium to low voltage distribution network, therefore the reference model CINELDI[2] is used to develop the network model and test the scenarios. The CINELDI MV reference system is a dataset that characterizes a typical Norwegian radial electric power distribution system that operates at 22 kV. A reference network commonly used for power grid analysis in Norway. It is a simplified representation of a real power system, including its limitations. Table II shows the main characteristic of the base reference system.

Table II: Main characteristics of the base system.

Parameter	**Value**
Number of nodes	124
Voltage level (base voltage)	22 kV
Base power	10 MVA
Number of load points	54
Total load demand, real power	6.407 MW
Total load demand, reactive power	2.106 MVAr
Power factor of loads	0.95 (lagging)

The simplified network is a lumped network model that comprises of only 50 nodes, in contrast to the actual CINDELDI network which has 124 nodes. For this paper, we utilize a model with 50 nodes at a nominal voltage of 22 kV, and obtain load profiles from these nodes for network analysis.

B. Electrolyser model

The water electrolyser is modelled as a flexible load where the scenarios are based on different loadings/percentage of maximum consumption for the electrolyser. The data for the electrolyser is taken from a NEL MC250 electrolyser system. MC electrolysers offer the M Series platform in a containerized format, enabling effortless outdoor installations. With the M Series PEM technology, the solution is reliable, turnkey, and requires minimal maintenance. This makes it suitable for various applications such as renewable energy storage, industrial process gas, and hydrogen fueling [17]. It is chosen a larger electrolyser as it must produce hydrogen for electrification of all fishing shores in the future, see locations in Figure 1.

For finding the maximum load the electrolyser will consume, the Net Production Rate is multiplied with the Average Power Consumption at Stack per Volume of H2 Gas Produced. The maximum loading for the electrolyser used for this analysis is shown in Equation 1, and the data is taken from [17].

$$246Nm^3/h \cdot 4.5kWh/Nm^3 = \underline{1107kW} \quad (1)$$

C. Scenarios

In order to assess the potential demand flexibility in the distribution network of Lofoten, several scenarios have been created. These scenarios take into account the anticipated electrification of the maritime sector in Lofoten, as well as throughout Norway and Europe in the years ahead. The scenarios examine the possible distribution grid conditions.

[2] Cineldi, https://www.sintef.no/projectweb/cineldi/

Scenario 0: To establish the reference scenario, the peak powers for the network model are chosen, which is called the Base Case. In this case, the water electrolyser is not connected to the distribution grid.

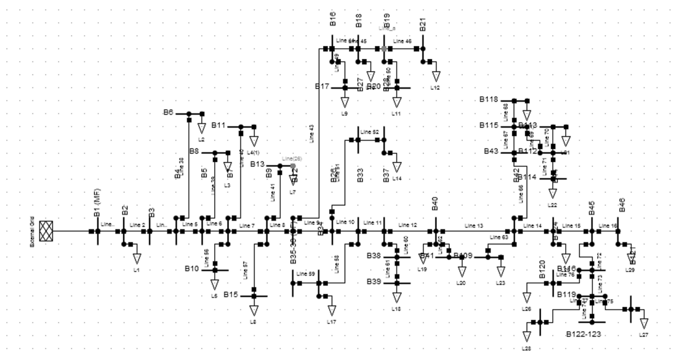

Figure 3: Base case scenario.

Scenario 1: Involves conducting an assessment of the location for the electrolyser. This assessment will include running load flow analyses for both the network system and the electrolyser, using peak loads to determine their respective capabilities.

Scenario 2: Involves connecting three Fast-charging Stations (FCSs) to the critical buses identified in Scenario 1. This presents an opportunity for the Lofoten area to develop a business related to the regional energy infrastructure being designed by ZeroKyst, which includes fast charging points. The FCSs will be centralized, high-power electric vehicle charging stations based on the values from the CINELDI Reference network. Each FCS will typically include 12-16 charging points with a capacity of $0.125MW$.

Scenario 3: Three FCSs and two Ferry charging Points (FCPs) will be linked to the critical buses identified in Scenario 1. Including ferry charging points is essential, as we are exploring the possibility of electrifying more ferries in the Lofoten area, which could offer exciting business opportunities in the future.

V. Simulation Result and Discussion

Figure 4 is the resulting voltage profiles for the 4 scenarios. Figure 5 shows the resulting loadings for the different lines in the network system. Table III is a summary of Total losses from the Base Case and then the increase in percentage from the base case compare to the other scenarios.

Table III: Total losses for the different scenarios.

Total Losses			
Base case	**Scenario 1**	**Scenario 2**	**Scenario 3**
0. 16 MW	$\uparrow 50\%$	$\uparrow 68.8\%$	$\uparrow 731\%$
0. 11 MVar	$\uparrow 54.5\%$	$\uparrow 72.7\%$	$\uparrow 736\%$

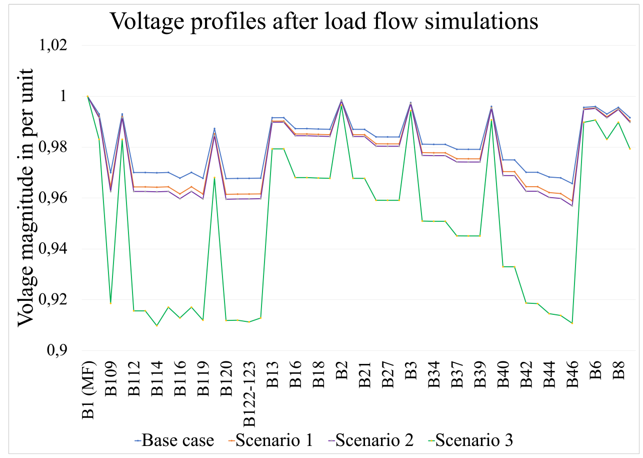

Figure 4: Voltage profiles for the different scenarios.

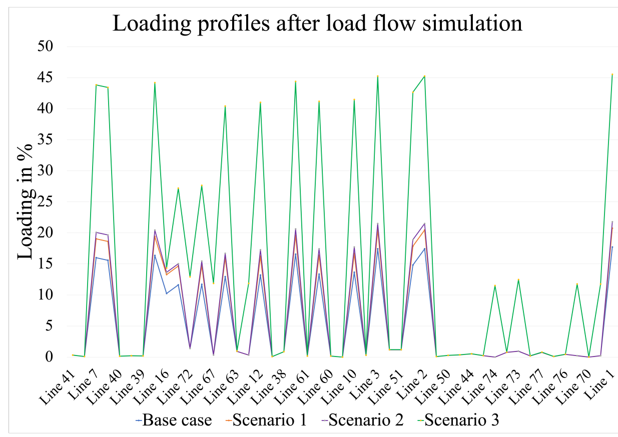

Figure 5: Loading for all the lines for the different scenarios.

Scenario 0: As can be seen from the legend in Figure 6 the load flow simulations show good system performance. The voltage level is within acceptable limits, indicating that the network is well balanced and the equipment is functioning correctly. Additionally, the loading is within the acceptable range, indicating that there is sufficient capacity to meet the power demands of the system without overloading or overstressing the equipment. These results suggest that the network model is operating efficiently and is capable of handling peak loads without compromising the reliability or stability of the system.

Scenario 1: Figure 7 reveals a notable area highlighted in light blue that is of critical importance. This area comprises buses 42-46 on the branch and the radials emanating from it. Fortunately, none of the buses within this critical zone exhibit voltage magnitudes below the minimum level of 0.94pu, indicating that the system is functioning as expected. The corresponding parameters listed in Table III show a 50% increase in total losses when compared to the base case. It is also evident from Figure 5 that the loading of the lines is higher than compare to base case.

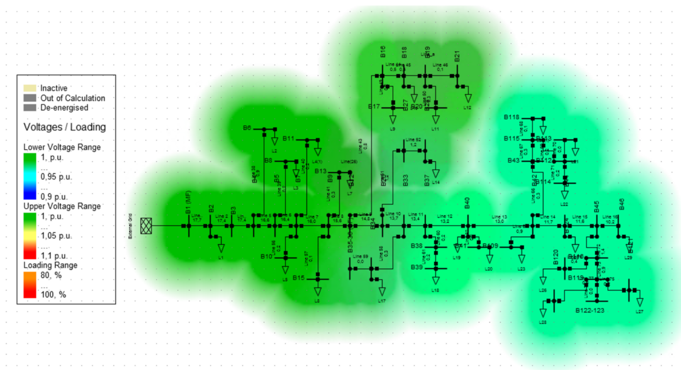

Figure 6: Simulation result for base case scenario.

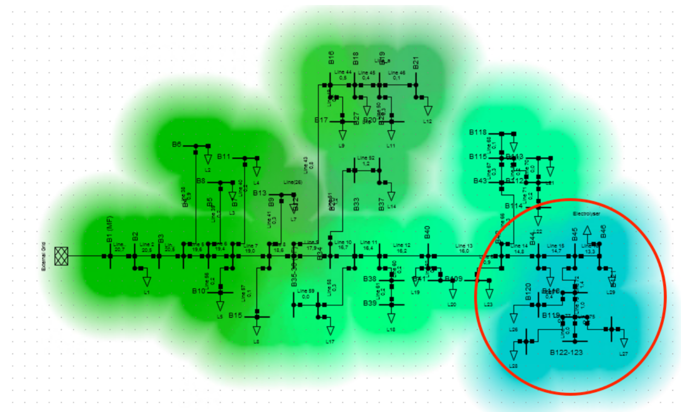

Figure 7: Simulation result for base Scenario 1 where the water electrolyser is connected at the end of the network.

Scenario 2: Figure 8 indicates an expansion of the critical area, depicted in light blue. Meanwhile, Figure 4 shows that although the voltage profile has decreased compared to both the Base Case and Scenario 1, it remains within acceptable levels (0.94-1.06pu). However, there has been a 68.8% increase in losses compared to the Base Case. Figure 5 reveals that the highest line loading is approximately 21%, suggesting that the network can accommodate such a load.

Scenario 3: Shown in Figure 4, the voltage exceeds the acceptable limit, indicating instability within the system. As a result, the scenario 3 is not technically feasible. In addition, Table III reveals a significant increase in total losses compared to the Base Case. Thus, connecting three FCSs or two FCPs is not a viable option. Further analysis of the system may be necessary to ensure stable and efficient operation.

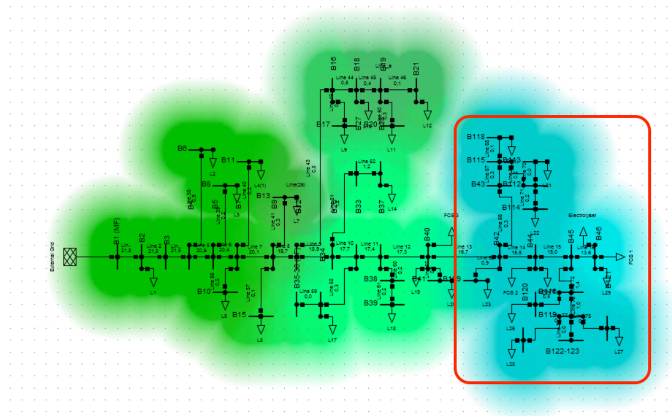

Figure 8: Simulation result for base Scenario 2 where 3 Fast-charging stations (FCS) is connected in the critical bus area.

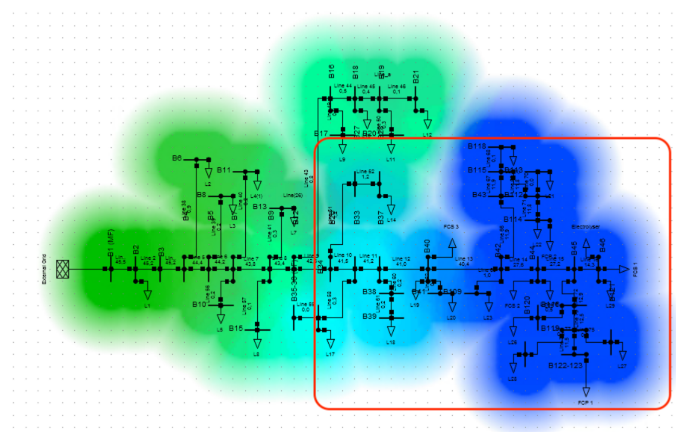

Figure 9: Simulation result for base Scenario 2 where 3 Fast-charging stations (FCS) and 2 Ferry charging points is connected in the critical bus area.

VI. Conclusion

Hydrogen play an important role in the transformation of power system towards electrification and operational flexibility. This work address distribution grid capacity challenge using hydrogen technology. Based on the proposed model, running various scenarios, it is possible to incorporate an electrolyser as a source of flexibility and estimate its impact on the distribution network. The results of the scenarios indicate that the system can effectively handle the implementation of the electrolyser even under maximum loading conditions. It also exhibits flexibility possibilities, as evidenced by the stable voltage and loading of the lines. Moreover, the study presents additional business prospects for the Lofoten region, as well as flexiblity solutions tested with maximum loading for the electrolyser. However, the instability observed in the last scenario limits the flexibility possibilities. Building upon the model presented in this paper, future research can leverage it as a foundation to develop a real network model with real data. Nonetheless, the electrolyser can be utilized alone for flexibility purposes or integrated with FCSs. These findings highlight the potential of the electrolyser technology in terms of flexibility in the Lofoten area, creating potential of flexibility services for system services to be provided to transmission and distribution system operators, to allow safe and reliable grid operations. From the various options currently investigated, electric-hydrogen technology demonstrating great potential in terms of lower energy costs for consumers/prosumers, lower emissions, and improving reliability and security of supply.

VII. Acknowledgement

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