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Subject: Request for Information (RFI): DE-FOA-0001655 -- H2@Scale (Hydrogen at Scale): Determining Research, Development, and Demonstration (RD&D) Necessary for Clean Hydrogen Production to Enable Multisectoral Deep Decarbonization

Prepared for: U.S. Department of Energy, Energy Efficiency and Renewable Energy

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Description: DOE seeks input on priority RD&D areas to enable deep decarbonization of industrial, transportation, and power generation sectors through wide-scale deployment of hydrogen. Given the broad scope of H2@Scale, and the need to engage many stakeholders to ensure the proposal's success, DOE is soliciting feedback on activities to advance the H2@Scale proposal in both the near and longer-term. This document provides a response to this request for information. Cavendish Energy suggests multiple important areas of exploration that can significantly advance H2@Scale and this particular request for information.

Background: The underlying capacity to produce hydrogen on-site in a scalable, controllable, environmentally benign, and economically viable manner currently eludes the reforming and electrolysis providers. Decreased costs associated with massive demand increases and general availability to the public is still in the unknown distant future with no clear roadmap. Numerous barriers need to be overcome before progress beyond limited pilots can be achieved.

Innovation is required, especially disruptive innovation to reconfigure the hydrogen markets in a manner that will provide abundant, reliable, sustainable supply at a price that will permit competition on a cost basis, and to facilitate hydrogen as the energy-carrier in numerous applications. Such innovation should address more than just the current two incumbent technologies (electrolysis and SMR) for the answers.

Substantial resources have been expended by industry stakeholders, federal labs, academia, government agencies, and others in positioning hydrocarbon reformation and electrolysis as the imagined solutions. Meaningful progress has been made as a result of this two-pronged focus. However, Cavendish Energy suggests that there may be nearly insurmountable obstacles associated with such an exclusively two-pronged approach. These include storage and transportation costs, hazardous materials concerns, regulatory requirements, and the lack of energy sustainability.

Cavendish Energy has developed a novel third mechanism for producing hydrogen from recycled aluminum at the requisite volumes, purity, reliability, sustainability, and economic viability. The underlying technology has been tested and demonstrated repeatedly with our advanced engineering partner the Gas Technology Institute (GTI) and our industrial partners. Cavendish Energy's process has been developed under significant secrecy to protect the intellectual property and is now ready for commercial development and deployment. The science behind the process is well understood and the research is well along, and Cavendish is now prepared to finalize the development and demonstrate the innovative approach.

The Cavendish Process provides clean, sustainable, affordable, and reliable hydrogen and valuable byproducts from domestic resources, and contributes to increased U.S. energy security, reduced criteria pollutants, and reduced greenhouse gas emissions. The Cavendish Process can provide on-site scalable volumes of sustainable, cost-competitive, environmentally benign hydrogen and salable byproducts including aluminum hydroxide, electricity, heat, and potable water.

The H2@Scale initiative will develop and enable the deployment of transformational technologies that produce and utilize green, low-cost hydrogen to achieve an economically competitive, deeply decarbonized future energy system across sectors. DOE seeks to identify research efforts that can enable the integration of hydrogen production with the electricity grid, as well as with process heat to enable deep decarbonization of end-use industries, and Cavendish offers an exciting opportunity.

I. Concept of H2@Scale

I.1 *What are the main drivers for your interest in H2@Scale (e.g. storage, ancillary services, potential synergy with other end uses, power-to-gas, revenue, etc.)?* The main driver for Cavendish Energy is providing low cost, on-site, scalable, controllable H_2 production on demand from recycled aluminum. Cavendish H_2 is low-cost, green, and sustainable and qualifies for California Low Carbon Fuel Standard (LCFS) credits and applies to the California RPS mandate.

I.2 *Are you already engaged in work aligned with the H2@Scale concept? If so, please describe.* Yes. Cavendish Energy has successfully developed and tested the H_2 production technology and has repeatedly demonstrated it for industry, government, and research partners. Cavendish has already produced at 1/10 scale in the Cavendish lab at the Illinois Institute of Technology (IIT) and the Gas Technology Institute (GTI), and the process is scalable. Further, these devices can be coupled together in parallel to produce any higher volumes desired – scalability has been proven.

I.3 *Can you conceptualize a collaborative H2@Scale RD&D project that will help to address your needs? If so please describe what it would entail.* The collaborative H2@Scale RD&D project would entail a Cavendish device producing 9,000 kg annually of H_2, 200,000 kWh annually of heat energy, and substantial quantities of aluminum hydroxide. The capital required is approximately $100K per device; RD&D requirements from H2@Scale would be approximately $2 million.

I.4 *In what applications (e.g. micro-grids) would a demonstration of fuel cell and/or electrolyzer integration with the grid be of interest?* The application would be an integrated coproduction facility producing H_2, electricity, heat, potable water, and aluminum hydroxide. The outputs would available to the mobile and stationary hydrogen markets, the electric grid, the chemical industry, and DOD tactical applications.

I.5 *What would you like to see in a large-scale demonstration? What scale would be most appropriate? Is the scale of interest seasonal?* As indicated, the appropriate starting scale is a plant producing 9,000 kg annually of H_2 – see 1.3. A larger plant capacity is feasible by simple direct scaling and/or combining several Cavendish devices. The plant is not seasonal: It produces all of its products on a reliable 24x7 basis.

I.6 *If you would like to see a large-scale demonstration, please specify what funding level would be appropriate. Please also include deliverables, metrics, and go/no go decision points.* The capital required is $100K per device: RD&D costs total $2 million. The deliverables would be substantial, low-cost, green, commercial levels of H_2, aluminum hydroxide, electricity, heat, and potable water. The metrics have been determined and are economically feasible, but are proprietary to Cavendish. The go/no go decision points would be at the scale-up of the Cavendish device and the initial production runs.

I.7 *What are the main challenges/issues/gaps that must be addressed before conducting a demonstration?* Technical challenges that must be addressed include scale-up design, hazards and operability review, continuous feed vs batch, test plan development and data acquisition, system design automation and controls development, material handling issues, prototype unit testing, and data analysis.

I.8 *Do you see a value proposition for end uses of hydrogen in both the near-term and mid/long-term? If so, please describe. If not please articulate why not.* Yes. End users of H_2 will have access to a reliable, low cost, on-site renewable source of H_2 that meets the purity requirement of the SAE J2719 Standard and is available for both mobile and stationary applications.

I.9 *Can you describe the cost at which a given application of hydrogen (e.g. power-to-gas) becomes attractive?* The on-site, delivered, unsubsidized cost of H_2 varies greatly by application and method of production. For example, research labs in Chicago pay $50 - $60/kg delivered, whereas the SMR plant costs per kg are much lower. For mobile applications and HFCVs, the H_2 on-site delivered cost must be $8 - $12/kg to be gallon gasoline cost equivalent (GGE), excluding all taxes. The current Cavendish H_2 cost is $10 - $11/kg (about $4.50/GGE), and the 2018 Cavendish H_2 cost estimate is about $7/kg H_2 (about $3.00/GGE) – which is competitive with the EIA forecast U.S. gasoline prices. The current Cavendish H_2 cost is at least an order of magnitude lower than H_2 from electrolysis and of the delivered cost of on-site H_2 from other sources.

I.10 *Would you be willing to share data if DOE were to fund a demonstration project? If so, what specific data?* Yes. Cavendish is willing to share all non-proprietary data with DOE.

I.11 *What data is most important to assess feasibility and applicability of the H2@Scale concept?* The most important metric is the on-site, delivered, unsubsidized all-inclusive cost of the H_2, electricity, and byproducts produced.

I.12 *What do you see as the appropriate and optimum role for the multitude of stakeholders, and any others not listed here? Stakeholders include national laboratories, the various industries involved, universities, public utility commissions (PUCs), state/local government entities, etc.* Stakeholders will play a key role. National laboratories can provide technical support, certification, and verification. Hydrogen vehicle manufacturers (including Toyota and Hyundai) will have access to H_2 for fueling stations. PUCs, state/local governments, and local industry and businesses will have access to reliable, peak-shaving electricity. Chemical manufacturers and other industries will have access to sustainable, U.S.-produced aluminum hydroxide. DOD will have access to a fuel source that is nonflammable, nonexplosive, and nonhazardous and is easily transportable.

I.13 *In addition to a technology demonstration, are there options to demonstrate innovative regulatory and/or policy ideas that would advance the H2@Scale concept? Please describe.* Yes. Cavendish devices can be used in fueling stations in California and other states. Cavendish devices can also be used in innovative policy initiatives designed to assist in the decarbonization of the industrial, transportation, and power generation sectors through wide-scale deployment of sustainable hydrogen. Further, Cavendish devices have numerous DOD tactical applications and can change the military's policy on transporting explosive and flammable fuels.

II. Leveraging Stranded Renewables, and Value-Added Applications for H_2

The business case for H_2 production can also be substantially improved through the development of value-add applications, and DOE would like feedback on RD&D that would enable hydrogen to better leverage renewable generation, and decarbonize industrial sectors:

IV.1. Not applicable.

IV.2. Not applicable.

IV.3. Not applicable.

IV.4. *In what manufacturing applications would use of hydrogen as a heat source be of interest?* Cavendish hydrogen has many immediate manufacturing applications. Hydrogen is currently used in many industries, including chemicals, food processing, metals, glass, and electronics. It is also used as a fuel in space applications and in analytical chemistry applications (such as gas chromatography, semiconductor fabrication, hydrogen braze furnaces, and fuel cell testing).

IV.5. *Are there innovations in chemical processes (e.g. conversion processes, membranes) that can be leveraged to create value-add applications for hydrogen?* The major innovation offered by Cavendish is the coproduction with hydrogen of aluminum hydroxide, which has numerous uses in the chemicals industries. The Cavendish Process byproducts offer valuable potential in the production of high-value specialty alumina for use in products, including ceramics, refractories, abrasives, glass, and flame retardants. Aluminum hydroxide [$Al(OH)_3$] is a valuable, saleable product that increases the commercial viability of the Cavendish Process. It is used in myriad products and applications, including alumina trihydrate (flame retardants, fillers, pigments), aluminous cement, activated alumina (absorbents and desiccants), chemicals (aluminum sulfate, aluminum chloride, aluminum fluoride, aluminum phosphate, and sodium aluminate) metal slag adjusters (smelter grade alumina), and calcined alumina (fused and sintered alumina, refractories, abrasives, ceramics, proppants, and welding flux).

IV.6. *Would you have an interest in a collaborative project demonstrating the ability of hydrogen production to de-risk investments in the development or operation of renewable resources? If so, could you please describe your interest?* Yes. Cavendish Energy would be interested in a collaborative project demonstrating the ability of hydrogen production to de-risk investments. Cavendish is interested in collaborative projects with various industrial partners, including chemical companies, hydrogen producers, hydrogen vehicle manufacturers, aluminum companies, and other potential collaborators. Cavendish is currently in discussion with potential industry collaborators.

IV.7. *What bridge markets do you foresee (e.g. deploying fleets of fuel cell vehicles) that could create a market for hydrogen produced from curtailed renewables?* Cavendish has targeted at least five near term bridge markets: hydrogen fueling stations for fuel cell vehicles; AC/DC backup power; combined stratification/regeneration truck systems; tabletop hydrogen for analytical chemistry and other applications; recreational stove systems, and DOD tactical applications.

Some additional input you could provide:

VI.1. *Are you working with hydrogen now or are you considering working with hydrogen? Why or why not?* Yes. Cavendish has been successfully producing sustainable, controllable, scalable hydrogen for three years in the lab.

VI.2. *What is an appropriate capital cost target for electrolyzers, fuel cells, and other relevant technologies that H2@Scale would leverage?* Current capital costs for relevant technologies can be justified with Cavendish produced hydrogen at the levels described in the answer to question I.9.

VI.3. Not applicable

VI.4. Not applicable

VI.5. *What specific studies and/or analysis would be valuable to the stakeholder community and specifically to your industry/organization to advance the H2@Scale concept?* Rigorous studies are needed of the current actual, unsubsidized, delivered, all-inclusive on-site cost of hydrogen per kg. Reliable data are very hard to come by.

VI.6. *In addition to DOE funding for the proposed RD&D activities, please list any other sources or potential sources of funding that may be leveraged for the proposed work related to H2@Scale (e.g. state funding, loans/financing, utilities, other policy/fee based sources of revenue, etc.).* Sources of potential Cavendish funding include state governments, foundations, and industrial and institutional stakeholders. Cavendish is in discussions with some of these.