Analysis of Advanced Hydrogen Production Pathways

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Contract Number: DE-EE0008084

Subcontractors:
- National Renewable Energy Laboratory (NREL), Golden, CO
- Argonne National Laboratory, Argonne, IL

Project Start Date: October 1, 2016
Project End Date: September 30, 2020

Overall Objectives

- Perform cost analysis of various hydrogen production and delivery pathways.
- Identify key cost and performance bottlenecks of the given pathways.
- Conduct deep-dive analyses and optimization studies on hydrogen delivery scenarios.
- Supply information from techno-economic studies to DOE for life cycle analysis.
- Respond to the scope and topic areas as defined by DOE.

Fiscal Year (FY) 2018 Objectives

- Completed a techno-economic analysis for a wire-wrapped steel vessel suitable for high-pressure cascade storage of hydrogen.
- Conduct a techno-economic analysis on the cost of transmitting energy: electrical transmission lines, gaseous pipelines, and liquid pipelines.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery and Hydrogen Storage sections of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan[1]:

D) High As-Installed Cost of Pipelines (Hydrogen Delivery)

E) Gaseous Hydrogen Storage and Tube Trailer Delivery Cost (Hydrogen Storage).

Technical Targets

Techno-Economic Analysis of a Cascade Storage System:

The 2020 DOE cost target for hydrogen storage for on-site hydrogen stations is \$600/kg H_2 (uninstalled).[2] These storage tanks have traditionally been large-diameter, thick-walled vessels of steel construction, with a pressure rating over 12,500 psi to allow fast-fill cascade refueling to 10,000 psi automotive storage tanks. As a result of their construction, the tanks are generally significant cost drivers for on-site hydrogen stations and the cost of a tank exceeds the 2020 DOE target. To meet the DOE 2020 on-site storage target, new tanks or new manufacturing processes will be required. To that end, Strategic Analysis, Inc. (SA) completed a techno-economic analysis focused on advanced designs for a steel-wire-overwrapped, Type I stationary hydrogen storage system that may lead to significantly reduced dispensing site hydrogen storage costs compared to the high-pressure storage FY 2015 target (\$2,000/kg H_2).

Comparative Techno-Economic Analysis for the Transmission of Energy:

The 2020 DOE target for delivered hydrogen is \$4/kg H_2 and encompasses the costs of hydrogen production, transmission, and dispensing. However, the cost of transmitting energy over long

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[1] https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

[2] The DOE target for hydrogen storage tanks/pressure vessels includes the cost of the pressure vessel, painting, cleaning, testing and a suitable mounting frame.

distances is largely unstated in the public literature yet is a crucial step in creating high-output, cost-competitive renewable energy “farms.” Consequently, an analysis was conducted to examine the transmission costs of a variety of energy carriers. Future analysis may then combine those transmission costs with the other elements of the full energy pathway to assess the delivered cost of hydrogen for comparison to the DOE targets.

FY 2018 Accomplishments

- Completed a techno-economic analysis for a wire-wrapped steel vessel suitable for high-pressure cascade storage of hydrogen.
- Completed an analysis of the cost of transmission of energy. This work has been compiled into a report and presented to DOE.

INTRODUCTION

Two main tasks were conducted in Year 2 of the project. The first task was a techno-economic analysis of Type I wire-wrapped pressure vessels. This analysis was initiated in Year 1 and finalized in Year 2, with documentation of the costs of the WireTough Cylinders, LLC, storage tank production process and a cost comparison for hydrogen storage. The documentation was provided to DOE after completion. The cost of hydrogen cascade storage tanks such as those used at hydrogen dispensing stations is generally considered to be a significant component of station cost. Hydrogen storage tanks at a station are generally used to hold and dispense hydrogen at pressures up to 12,500 psi. Traditionally, the tanks used for these storage applications are large, thick-walled steel vessels. Due to the thickness of the steel required to hold such high pressures, these tanks are expensive and will not meet the DOE 2020 cost targets for on-site storage. New developments for manufacturing suitable high-pressure storage tanks, such as the wire-wrapping steel tanks as proposed by WireTough, could significantly reduce the cost of hydrogen storage at a dispensing station. The analysis conducted by SA focused on projecting a manufacturing process suitable for fabricating up to 3,000 tanks per year and creating a cost model to predict the cost of manufacturing the tanks.

The second Year 2 task of the project was to conduct a cost analysis of energy transmission for various transmission methods and energy carriers. Energy transmission costs are of particular interest when considering large-scale, remote renewable energy production (solar, wind, biomass) and long-distance energy transmission (1,000+ miles) to population centers. Energy transmission can be accomplished via electrical power lines, gaseous pipeline, or liquid pipeline, although depending on the ultimate end-form of the energy, conversion costs may be incurred. Until recently, little data has been published in the scientific literature regarding the cost of transmission of energy. Transmission cost has traditionally been blended with some combination of production, conversion, and/or dispensing cost, thereby making it difficult to compare transmission-only cost. Comparing transmission costs for various methods and fuels is also difficult due to the different cost units used by various data sources. To achieve a fair comparison of transmission costs, SA examined a variety of cost modeling methodologies and data for electrical transmission lines as well as oil and natural gas pipelines. These cost models were modified by SA to create a new cost model with a consistent set of physical, operating, and financial assumptions. The results of the modified SA cost model provide an equitable comparison of transmission cost, considering both construction cost ($/MW-mile) and total transmission cost ($/MWh).

APPROACH

Techno-Economic Analysis of a Cascade Storage System

To properly analyze the hydrogen storage vessel developed by WireTough, a ground-up Design for Manufacture and Assembly (DFMA) cost estimation methodology was used. The DFMA process breaks down each manufacturing process step into the material cost, equipment cost, labor cost, utility cost, and tooling cost. The equipment cost is the capital cost of any production equipment, amortized over the life of the production equipment, with extra cost provisions made for maintenance and repair. Key process parameter values for the DFMA analysis were provided by WireTough and further supported by material and equipment cost quotations from various manufacturers. All process parameters and assumptions were reviewed by WireTough for accuracy and appropriateness. While the DFMA analysis focused on the vessel, costs were also tabulated for the complete cascade storage system (i.e., mounting brackets, lines, valves). The finalized results were compared to the DOE cost targets for hydrogen on-site storage.

Comparative Techno-Economic Analysis for the Transmission of Energy

The energy transmission cost analysis examined six transport systems: electrical transmission line; liquid pipelines carrying oil, methanol, or ethanol; and compressed gas pipelines carrying either natural gas or hydrogen. This cost analysis focused solely on the cost of transmission and thus does not consider the method of production for any energy carrier (i.e., electricity, hydrogen, oil) or the cost of conversion (i.e., hydrogen production, natural gas combustion for electrical production). The pipeline and electrical line cost models used in this work are derived from published data sets on the construction of pipelines and electrical lines in the

United States. New construction of transmission lines or pipelines was assumed. The cost model for the electrical transmission line was developed by the Black & Veatch Corporation for use by the Western Electric Coordinating Council [1]. Two cost models for determining the capital cost for the construction of gas pipelines were considered. The first is a study by Rui et al. [2], which examines the capital cost of 412 on-shore pipeline construction projects between 1992 and 2008. The second cost model, described by Brown et al. [3], uses 30 years of on-shore natural gas pipeline cost data, ranging from 1980 to 2010. Both models are derived from data published by the Oil and Gas Journal.

A total transmission distance of 1,000 miles is assumed for all systems. This is approximately the distance between St. Louis, Missouri, and New York City, New York, and is meant to represent long-distance transport over a variety of terrains, from a large energy production site to a large energy consumption site. All calculations are completed with a utilization factor of 100%, indicating that the given transmission method is being used continuously at nominal design capacity. While 100% utilization is unlikely for real-world application, such an assumption provides the lowest levelized cost of energy transmission for all carriers and allows for accurate comparison of the cost of transmission between electrical transmission lines and fuel pipelines. Sufficient cost breakdown detail is given to allow the reader to estimate capital costs ($/mile-MW) at other utilizations. The total cost of transmission for each transmission method includes an amortization of the capital cost, as well as annual expenses for fixed and variable operating costs, and is reported in $/MWh. A Monte Carlo analysis was performed as a method to determine the likely cost of energy transmission by a given method. The range of values returned by the Monte Carlo analysis was taken to be the 90% confidence interval and is marked as the bounds for error in the analysis results.[3]

RESULTS

Techno-Economic Analysis of a Cascade Storage System

The wire-wrapping process begins with a 30-foot-long steel liner rated for approximately 6,600 psi.[4] The liner is carried by crane to a wire-wrapping station, which combines 24 steel wires into a wire tow band that is then wrapped around the cylindrical section of the liner. The end domes of the liner are not covered in the wire wrapping process. Epoxy is applied to the wires as they are wrapped. The epoxy protects the wires from corrosion, provides added strength and rigidity, and prevents wire movement during pressure cycling. The outer layer of wires is taped with non-adhesive tape and then covered with epoxy. The assembly is next sent to an oven for partial epoxy curing, followed by a full cure at room temperature. The pressure vessel is then put through an autofrettage process to impart internal residual compressive stress. Finally, the pressure vessel is painted with an ultraviolet-resistant paint.

The vessel analysis was extended to develop a suitable storage cost for use in H2A cases. To do this, a theoretical balance of system (BOS) was developed to formulate a cost for a storage system that could be used at a hydrogen forecourt station. The theoretical station would have a bank of three sets of two tanks and feed to six dispensers (See Figure 1). When possible, the components required for the BOS (e.g., valves, pressure relief devices, thermocouples) were quoted by manufacturing companies. When price quotes were not available, SA used historical data to generate component pricing. The BOS also includes projected costs for installation, markup, and component assembly and testing. The combination of the storage vessel prices and the BOS prices can then be used as a total system cost for analysis of the delivered price of hydrogen.

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[3] The cost model used for electrical transmission was not well suited to Monte Carlo analysis and the error was thus marked at +/-50%. This range is in keeping with data reported in the literature [4–6].

[4] For clarity within this report, the solid-metal-walled pressure vessel is called a liner, while the completed, wire-wrapped product is termed a pressure vessel.

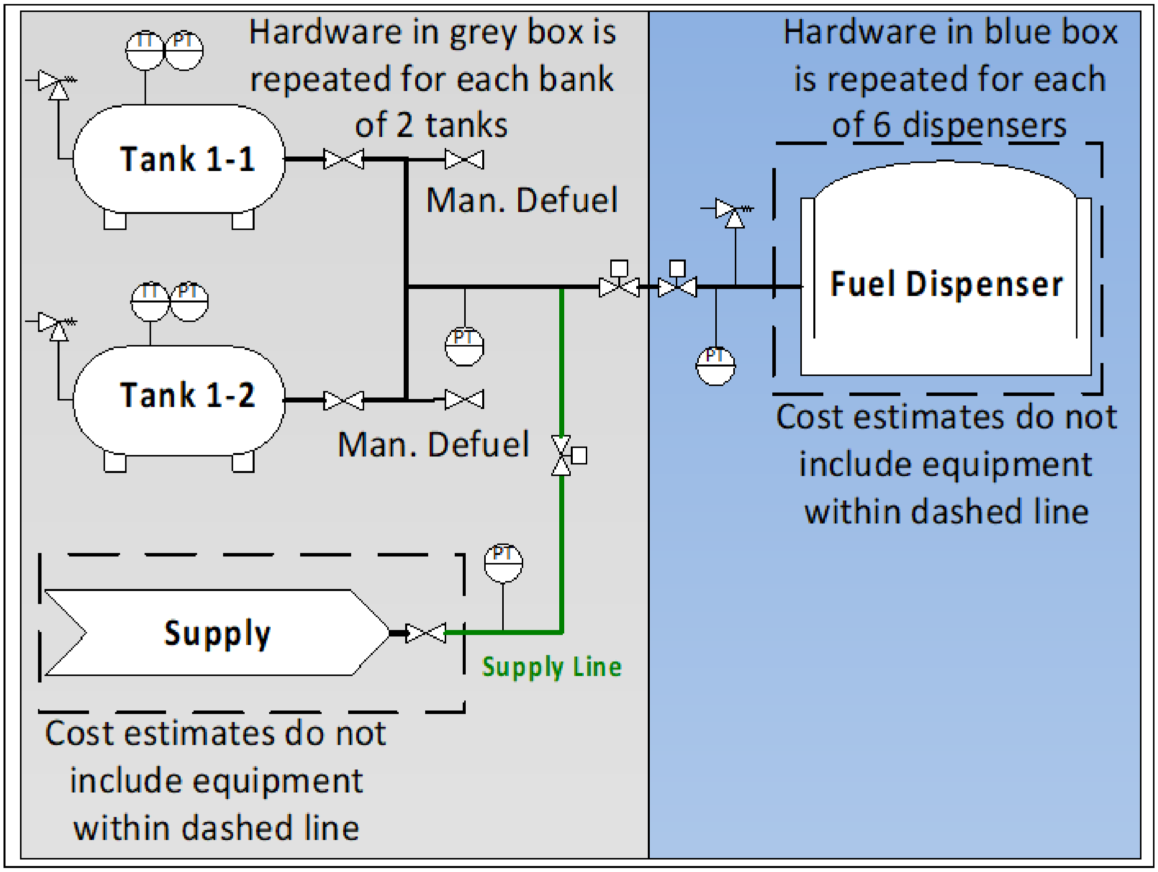

Figure 1. A section of the dispensing system modeled. Diagram shows the system and BOS for two high-pressure tanks and one dispenser. The complete modeled system is six tanks, broken into three banks of two tanks, with each bank feeding into any of six dispensers. All hardware presented in the gray box is repeated for each bank of two tanks. All hardware presented in the blue box is repeated for each of six dispensers.

The projected price (after markup)[5] of the pressure vessel (as defined by DOE) at low production volumes, as it is currently manufactured, is approximately \$803/kg H_2 (\$28,145/unit), based on a one vessel per day production rate. At higher production rates and process adjustments to account for automation, the projected price drops to less than \$593/kg H_2 (\$21,000/unit). When compared to DOE storage cost targets, the wire-wrapped vessels show significant improvement over the FY 2015 targets and approach the FY 2020 cost target of \$600/kg (see Figure 3).[6] The projected costs are also lower than the cascade storage tank prices used within the H2A models.

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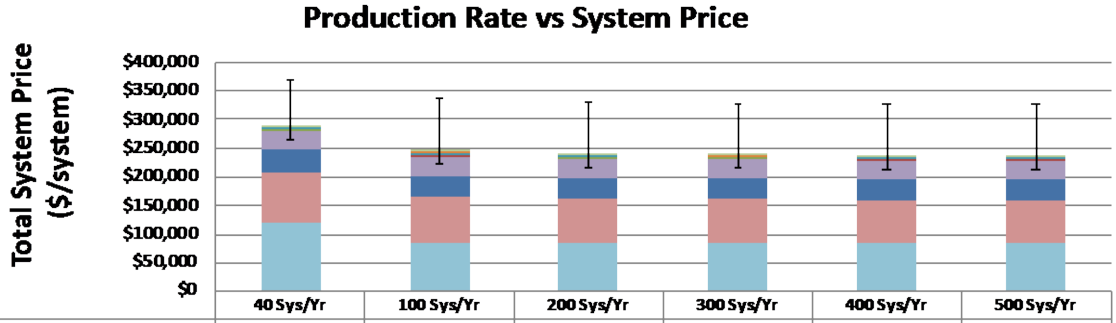
[5] A markup rate of 25% (at all production rates) was used to translate manufacturing cost into expected sales price (inclusive of company profit, overhead, general and administrative expenses, etc.). This rate is based on information garnered from the annual report of a high-volume pressure vessel manufacturer, Hexagon, and is extrapolated from the company's publicly reported gross margin and cost of goods sold. While markup rates can vary substantially company to company, even within an industry, Hexagon is judged to be an industry standard in hydrogen and compressed natural gas storage vessels, and thus is thought to be an appropriate markup rate benchmark.

[6] In order to make direct comparison to the DOE targets and align with the DOE terminology for stationary gaseous hydrogen storage costs, the term "tank" is used in Figure 3 to describe the WireTough pressure vessel. Further, "price" and "cost" are used interchangeably for Figure 3, as the purchase cost to a hydrogen forecourt station for a high-pressure storage tank is identical to the price WireTough would charge for its product. A table of DOE's target prices for hydrogen storage, along with descriptions of the components in question, can be found here: https://energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-delivery.



	40 Sys/Yr	100 Sys/Yr	200 Sys/Yr	300 Sys/Yr	400 Sys/Yr	500 Sys/Yr
🟩 System Assembly	$1,330	$1,019	$915	$881	$915	$895
🟦 Inspection	$79	$79	$79	$79	$79	$79
🟧 Paint Booth	$825	$3,919	$1,983	$1,338	$1,015	$822
🟦 Hydro Test	$3,028	$2,176	$1,892	$1,797	$1,749	$1,835
🟪 Final Cure	$496	$496	$496	$496	$496	$496
🟩 Oven Cure	$1,983	$1,812	$1,640	$1,583	$1,640	$1,606
🟥 Tape Winding	$976	$975	$975	$975	$975	$975
🟪 System Installation	$33,128	$33,128	$33,128	$33,128	$33,128	$33,128
🟦 Wire Winding	$39,566	$36,689	$35,671	$36,010	$35,671	$35,875
🟥 Balance of System (BOS) Items	$87,741	$82,787	$80,059	$78,778	$77,982	$77,453
🟦 Liner Price	$120,000	$82,500	$82,500	$82,500	$82,500	$82,500

Figure 2. Predicted cost of producing Type I wire-wrapped hydrogen vessels at different annual production rates

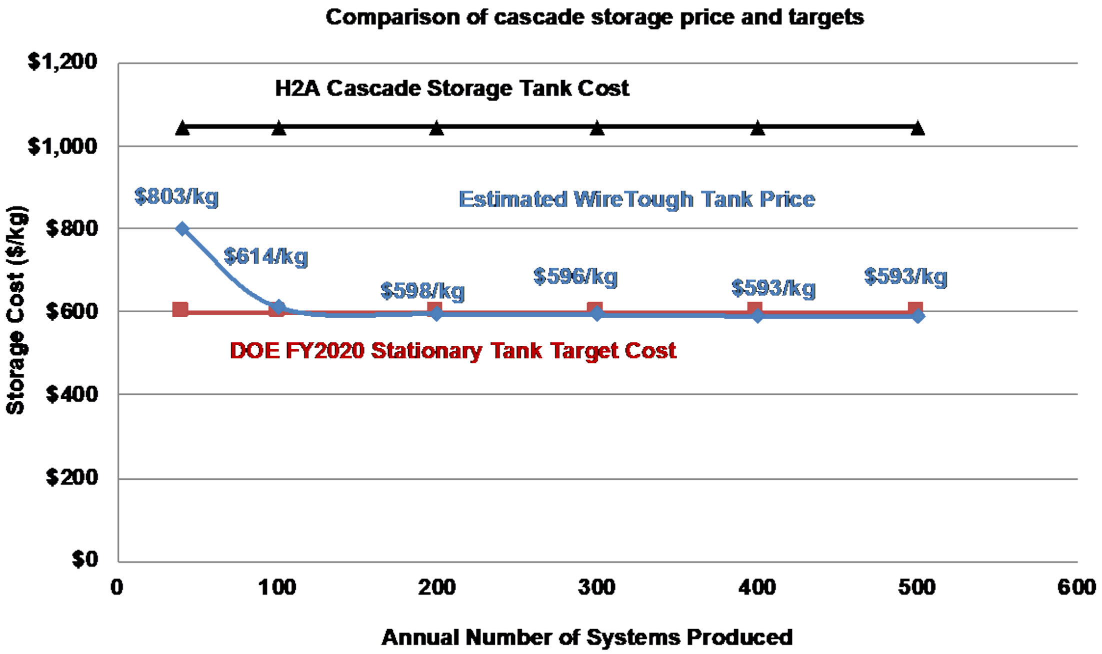


Figure 3. Comparison of wire-wrapped pressure vessel cost projections to the DOE target

Cost projections for the complete cascade storage system, including BOS, ranged from $1,203/kg H_2 to $958/kg H_2. The limited variation in costs at production rates between 240 and 3,000 pressure vessels/year is a result of a constant liner cost being used at each of those production rates. With such a dominant cost being held constant at different production rates, the variation in total cost with varying production rate is minimized.

Comparative Techno-Economic Analysis for the Transmission of Energy

Electrical transmission is actually the highest transmission cost among the six analyzed energy carriers and is nearly eight times greater than the cost of transmitting hydrogen via a pipeline. This is notable as hydrogen is the most expensive chemical fuel to transmit of the five fuels analyzed. The chemical fuels with the highest energy densities are the least expensive to transmit (See Figure 4). Wide error bars are present in Figure 4 for the pipeline costs and are a direct result of the wide variation of pipeline capital cost in the literature: Brown et al. costs [3] are 3.5 times greater than those of Rui et al. [2]. Further uncertainty stems from the location of construction (up to a 44% cost variation compared to the average cost).

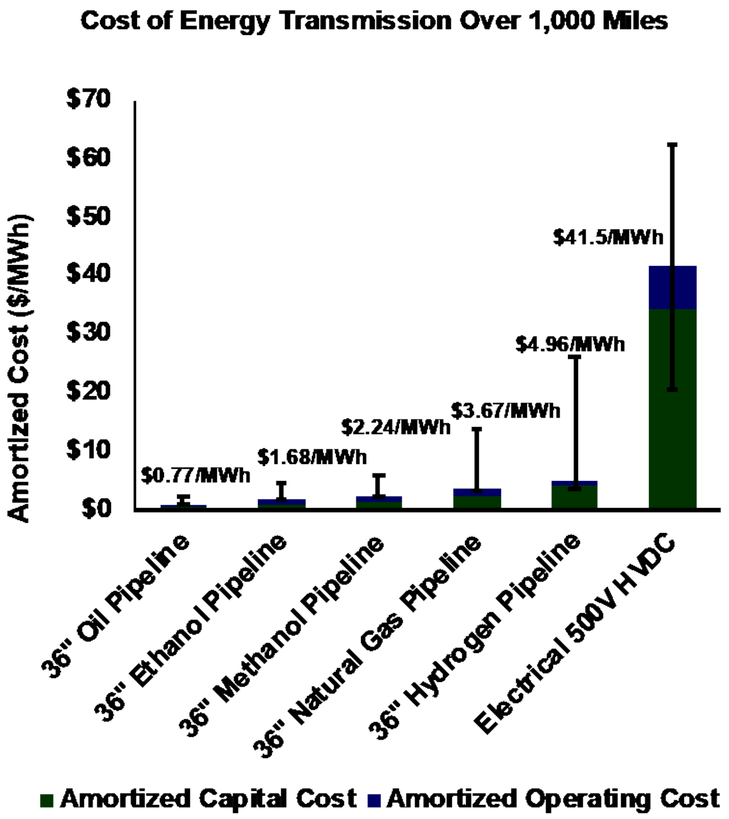


Figure 4. Amortized costs for each method of transmission analyzed

CONCLUSIONS AND UPCOMING ACTIVITIES

Techno-Economic Analysis of a Cascade Storage System

The WireTough wire-wrapped hydrogen storage system appears to be a cost-effective alternative to Type I tanks for stationary high-pressure applications. Preliminary analysis projects a pressure vessel cost of ~$600/kg of stored hydrogen (uninstalled), achieving the 2020 DOE target of $600/kg and surpassing the DOE 2015 status cost of $2,000/kg (See Figure 3).

Comparative Techno-Economic Analysis for the Transmission of Energy

The energy transmission analysis offers a new perspective on the cost of transmitting energy and indicates that the cost of transmitting hydrogen through a pipeline is actually less than the cost of electrical transmission on a $/MWh basis. Liquid fuels transmitted by pipeline are even less expensive. Future analysis should combine these transmission cost results with the cost for production and energy conversion (if needed) to assess the full cost of each production-transmission pathway.

FY 2018 PUBLICATIONS/PRESENTATIONS

1. Brian D. James, Cassidy Houchins, Genevieve Saur, Jennie M. Huya-Kouadio, and Daniel A. DeSantis, "Analysis of Advanced H_2 Production Pathways," presented at the DOE Annual Merit Review Meeting, 14 June 2018, Washington, D.C.

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