Project Innovation

Sustainable Operations Planning and Location Vetting for the Southwest Virginia Energy Park

— Final Report —

Issued October 15, 2021 to the
LENOWISCO Planning District Commission

Coalfield Strategies
Marshall Miller & Associates
Thompson & Litton
HDR

MEMO

To: Duane Miller, Ex. Dir., LENOWISCO Planning District Commission

From: Will Payne, Managing Partner, Coalfield Strategies, LLC

Date: October 15, 2021

Re: **Project Innovation Final Report Overview**

On behalf of our entire team, I want to thank you for the opportunity to study sustainable operational models and possible site locations for the "Southwest Virginia Energy Park" (working name), the subject of Project Innovation. This concept has been incubating for the past five years thanks to the vision and leadership of internationally known energy scientist Dr. Michael Karmis, director of the Virginia Center for Coal and Energy Research. We are now moving quickly toward launching the private entity and positioning it as a unique proving ground for cutting-edge energy projects. While a name and an identity have been established for the operation, for the purposes of this report, we will refer to it as the "Energy Park". Unlike traditional research facilities, the Energy Park's land *is* the lab, a differentiating factor that serves as a significant competitive advantage. We are grateful to the GO Virginia Region One Council and the U.S. Economic Development Administration for providing the funding to complete our work. As a result of this effort, planning for an implementation project is currently underway.

Background

Southwest Virginia has a legacy of driving energy production and manufacturing, with its key traditional role in the extractive economy. Metallurgical coal helped build America, while wells drilled over 60 years ago still produce natural gas today. As the United States moves toward carbon-neutral energy and our traditional industries decline as a result, Southwest Virginia has the opportunity to continue as a leader in energy. The Energy Park will focus on renewable, clean and zero-carbon projects, establishing the region as the energy innovation capital of the East Coast.

Project Innovation, the InvestSWVA initiative powering the Energy Park, emphasizes the importance of thinking outside the box as the first factor in sustaining the region's energy leadership position. Project Innovation integrates innovative research, workforce development and economic development under one umbrella. The Energy Park, the first of its kind in the United States, will be the vehicle for innovation and business investment in Southwest Virginia. It will host companies that are interested in studying, perfecting and eventually commercializing their intellectual property. The

Energy Park will provide land, labs and scientific assistance to innovators in the energy industry. The region will benefit from this activity as the Park provides assistance in commercialization to the private sector, a key value-add that will encourage investment in and attract new industries and jobs to Southwest Virginia.

Beyond Southwest Virginia's history, its unique set of assets – including more than 100,000 acres of previously mined property, more than 9,000 gas wells, numerous mine cavities, and boundless water – makes the region the perfect setting for companies using the Energy Park to focus on four key areas of research: Electricity Generation, Geoenergy, Going Digital and the Circular Economy. Electricity Generation research addresses renewables, storage technology, carbon capture and high-efficiency, low-emission technology. Geoenergy addresses any energy that comes from the earth, such as geothermal or eco-friendly coal or natural gas energy production. Going Digital research addresses strategies for making energy delivery systems and facilities more efficient, while Circular Economy research addresses options for end-of-life strategies for renewable generation components and the remains of the fossil fuel industry.

The Energy Park also embodies a commitment to education, particularly STEM. This education component is at the heart of the plan to grow the Energy Park, with programs to emphasize smart energy technologies studied through partnerships with local schools and hands-on experiences, regional competitions, and summer learning opportunities. The education component is critical, as it addresses the preparation of the region's workforce for new energy jobs that are created by the Energy Park's activities.

<u>Attachments</u>

In lieu of repeating 153 pages of findings in this overview memo, I have attached three comprehensive reports that detail the collective work of Project Innovation's greater team.

The process began with a team of 12 paid undergraduate student interns from Virginia Tech's Pamplin College of Business. These students performed a landscape analysis of science and innovation research parks in the United States and around the globe, with an emphasis on energy parks. The students were tasked with bringing their creative ideas to the table in order to identify revenue streams and build for long-term sustainability.

The next phase involved William & Mary's Mason School of Business. The university's Corporate Field Consultancy team synthesized the Virginia Tech data and found that the majority of parks are nonprofit organizations with varying sizes and types of governance structures. Many parks derive revenues from renting and leasing space, grants and business incubation services. The parks target a few different customer segments, the most significant being multinational corporations, research institutes and startups. Finally, the parks overwhelmingly fall under two value proposition categories, despite having many other supplementary propositions: supplying the services necessary for a business to run and giving newer businesses and entrepreneurs the resources to succeed that they otherwise might not have.

The Corporate Field Consultancy team also applied Alex Osterwalder's Business Model Canvas in designing a viable business model for the Energy Park. To assist in constructing the design, the team conducted primary research among professionals with knowledge of the energy industry, pairing it with a survey sent to more than 200 venture capital firms. The most common model for science and technology parks is a nonprofit structure that targets multinational corporations, research institutes and/or startups. The Energy Park instead would use rent, grants, and/or incubator programs for revenue streams to deliver on a value proposition of providing the space and resources necessary for an entrepreneur or business to prove an idea or accelerate its operations.

The Corporate Field Consultancy team determined that the Energy Park should target energy companies and mid-to-late-stage startups as its primary customer segments, enticing them with the value propositions of land, a well-connected network, scientific expertise and a community of people both committed to one common vision and willing to collaborate. Furthermore, the team determined that the Energy Park should partner with venture capital firms, governmental entities and research institutions to create a robust web of resources. Those partners will be able to provide resources that include everything but land, including capital, connections, researchers and the ability to commercialize ideas.

Finally, Project Innovation vetted locations in Southwest Virginia for the Energy Park. Many potential sites were visited, reviewed and considered, as the development of the Energy Park will likely be an incremental building process that will take place over a period of time – requiring a site that enables scaling in phases. Likewise, while the Energy Park may have a "main" facility, it is likely that satellite facilities will develop as a result of site availability and capability. A trio of professional firms, including Marshall Miller & Associates, Inc., HDR and Thompson & Litton, completed a comprehensive analysis of sites. The team determined that the development timeline of the Energy Park must be focused yet flexible in order to take advantage of both anticipated and unexpected opportunities. Further efforts to progress the Energy Park concept must include continued landowner and potential investor relationship development. Partners may include electric utility companies, alternative energy companies, land management companies, mining companies, government agencies (federal, state, and local), universities and private landowners.

Next Steps

As previously mentioned, implementation of the Energy Park is underway. Recent news detailed our first major announcement – a $975,000 AMLER award for the acquisition of land and for infrastructure improvements necessary for a planned renewable energy project on a series of previously mined properties. In addition, our team is in the process of establishing a 501c3 nonprofit entity with a board of directors to govern the Energy Park and guide its operations. Michael J. Quillen has graciously accepted the role as chair of the board, Dr. Michael Karmis will serve as senior technical advisor, and the Coalfield Strategies team will lead strategy and project development.

We also look forward to continuing to leverage the expertise of the Southwest Virginia Energy Research and Development Authority. The entity's enabling legislation states a goal of assisting technology research and promoting the creation of the Energy Park. The Authority's members and strategic partners have played a key role in the development of our major projects thus far, including Project Oasis and Project Energizer. Furthermore, I want to offer a special thanks to Delegate Terry Kilgore and the late Senator Ben Chafin for establishing the Authority in 2019 and for understanding the need for a private entity to drive renewable energy-related research, deployment and manufacturing. Our team is grateful for our extensive public sector partnerships, and we also recognize the complementary nature of those relationships. Therefore, we acknowledge that the Energy Park's private operational model is essential, because it allows us to move at the speed of research and business unencumbered by bureaucratic and political distractions.

Acknowledgements

A number of individuals and organizations in addition to those already mentioned contributed to this project. I would like to extend our gratitude to the following for their contributions to the success of this project:

- The LENOWISCO Planning District Commission team, including Jimmy Adkins and Frank Kibler, who had a hands-on role in securing funding and shepherding this project with GO Virginia and the U.S. Economic Development Administration.
- GO Virginia Region One's Kalen Hunter and Robyn Lee.
- U.S. Economic Development Administration's Lauren Stuhldreher.
- Members of the Southwest Virginia Energy Research and Development Authority, including Chair Mike Quillen and Vice Chair Dr. Kris Westover.
- The team at the Virginia Department of Energy, formerly the Virginia Department of Mines, Minerals and Energy, with special thanks to Will Clear and Daniel Kestner for coordinating the agency's expertise for location vetting.
- The Virginia Tobacco Region Revitalization Commission.
- The Honorable Elizabeth McClanahan, former Dean of the Appalachian School of Law.
- Representatives from Appalachian Power and Dominion Energy, key private sector partners in the development of the Energy Park.
- InvestSWVA's legislative co-chairs Delegate Terry Kilgore, Delegate Israel O'Quinn, Senator Todd Pillion and Senator Ben Chafin facilitated conversations with key partners and stakeholders over the last five years.
- Dr. Vicki Ratliff of Mountain Empire Community College.
- Dean Robert Sumichrast of Virginia Tech's Pamplin College of Business.
- Virginia Tech's Pamplin College of Business students: Trevor Flanary, Brittany Oliver, Haoyang Shao, Carly Wright, Jamie Burnette, Fernando Anduaga, Elena Boitnott, Huixian Lian, Tu-Nam Nguyen, Jonathan Lee, Natalie Ruffner and David Probst.
- William & Mary's Mason School of Business Corporate Field Consultancy team, including students Max Baldwin, KC Malone, Ekansh Mittal and Cara Simpson along with advisors Graham Henshaw, Ron Johnson, Ed Odachowski and Terry Shannon.

- The location vetting teams of Marshall Miller & Associates, Inc., HDR and Thompson & Litton.
- Mary Trigiani for strategic advice.
- InvestSWVA's strategic advisors at Hunton Andrews Kurth LLP's Global Economic Development practice, including Todd Haymore, Lee Downey, Taylor Keeney and Myles Louria.

We look forward to working with you and the LENOWISCO team in the next phase of the Energy Park's implementation. Please let me know if you have any questions.

Summary of Virginia Tech Peer Science and Innovation Park Research Reports
William & Mary Mason School of Business
Corporate Field Consultancy
Coalfield Strategies, LLC

Executive Summary

Over the past few weeks, the team assigned to conduct consulting work for Coalfield Strategies, LLC has completed an extensive synthesis of information received early in the process of this project. This information came in the form of 24 reports about science and innovation parks around the world from a group of 12 Virginia Tech undergraduate students in the university's Pamplin College of Business. The team found that the majority of parks are nonprofit organizations with varying sizes and types of governance structures. Many parks derive revenues from renting and leasing space, grants, and business incubation services. The parks target a few different customer segments, the most significant being multinational corporations (MNCs), research institutes, and startups. Finally, the parks overwhelmingly fall under two value proposition categories, despite having many other supplementary propositions: supplying the services necessary for a business to run and giving newer businesses and entrepreneurs the resources to succeed that they otherwise might not have. The following report and appendix give a more detailed synthesis regarding the team's research and the reports from the students.

Introduction

Coalfield Strategies LLC recently employed 12 undergraduate Virginia Tech students in the Pamplin College of Business to assist them in completing research on 24 intriguing examples of Innovation and Technology parks around the world. The reports provided great value that allowed the team to gain insights on the competitive environment of the science/innovation park industry. The consulting team examined these 24 parks, 90% of which have a direct vested interest in science and technology. After reading each of these reports, we developed a series of research topics that propelled us into the goals outlined for Phase One of the project in the Work Plan submitted earlier in the process. The team whittled down those research topics - of which there were many possibilities - into four broad points to guide our synthesis: governance structure of the parks, revenue streams utilized by the parks, the clients/customers that each park targets, and the value propositions of each park.

This document gives a detailed look into the research the team has performed in synthesizing these reports. The document is subdivided based on those research topics, with plenty of supplemental research and data found in the appendix.

Governance Structure

Entity Type

Only parks located in the United States were considered in the review of business entity types as business entity formation can vary greatly among countries. Of the 14 research parks located in the United States, 12 operate as a 501(c)(3) non-profit corporation. Three of those twelve have split off part of their business operations into a separate for-profit LLC. An additional 2 of the 12 nonprofits are also overseen by a government authority. Two parks are solely governed by academic institutions (Figure 1).

Leadership Teams

Information on the leadership team was available for all but six of the international parks. The most common leadership structure included both a management team and a board of directors. Management teams range from 1 to 14 members, with a median of 4.5 members. Information on Boards of Directors was only available for domestic parks. All but two parks are overseen by a board of directors, with one park - the Sanford Underground Research Facility (SURF) - having two distinct boards. One board is appointed by the governor of South Dakota and the other is managed internally. The median size board of directors is 9 members. There were two large outliers, as two parks had boards of directors of 23 and 50. The information regarding these leadership teams can be found in the appendix in Table 1.

The management teams generally include staff in charge of general business operations, finance, and marketing. However, some teams have more specific roles. For example, the University City Science Center in Philadelphia includes Vice President roles in Real Estate, Advancement & Strategic Initiatives, and Ecosystem Development.

Boards members come from a variety of backgrounds - many of the parks form their own boards to allow for various public and private stakeholders to have representation in the decision-making of the parks. Some boards are created through local law, as with the Central Florida Research Park and SURF.

Partnerships

Strong partnerships are an integral part of all research parks' business models. Many parks boldly display strategic partnerships as a way to showcase additional value these partnerships may add to customer segments. Common partner groups include support for businesses such as startup accelerators, incubators, and investment groups. Local government agencies, universities, and non-profit organizations relating to the parks' central functions are also common (Table 2).

Revenue Streams

While the Virginia Tech reports identified research and innovation parks that covered a wide range of geographical regions and activities of concentration, the revenues generated within these parks did not vary significantly. In total, the research found 11 different forms of revenue streams, with an average of 2.5 revenue streams per park across a range of 1 to 5 streams. All the data described in the following paragraphs can be found in Figures 2 and 3.

The majority of parks generate portions of their revenues from some type of rent or lease agreement with tenants. Some parks rent space by the square foot, some rent by the room, and some rent based on the type of activities the tenant wishes to undertake. But, in total, 21 out of the 23 parks (87%) have some kind of a rent aspect included in their revenue streams. The two that did not rent space were SURF and the Purdue Research Park. These facilities greatly benefit from having support from donors, government and university partners.

Following rent/lease activities, grants (43%), business incubators (35%), revenues from taxes and utilities from tenants (26%), and private donations (22%) make up the next four most common streams. Many parks have some kind of a mix of all of these, along with their rental activities. The parks that derive revenues from taxes and utilities are worth mentioning due to their uniqueness as well. They are able to make revenues this way by acting as faux-districts/counties/towns for the area in which they are located. They operate the park as if the park itself was its own geographical entity, and thus are able to pull these expenses from their tenants.

The final group of revenue streams is varied, but also has some intriguing options: corporate partnerships, university funding, and venture capital partnerships are revenue streams in three parks each, and two parks each derive revenues from membership programs and events/competitions. However, a significant revenue stream in this class that could be relevant to the Southwest Virginia Energy Park comes from land leases and/or development opportunities. Three parks incorporate this into their revenue model by leasing or selling land to companies looking to either develop a building on the land, use the land for research purposes, or use the land for whatever other activities they might have in mind.

More detailed descriptions of each park's various revenue streams can be found in Table 3. In summary, though, the parks have all adopted their own unique ways that allow them to make money. However, as mentioned above, one almost-constant is the use of some kind of renting building space, along with receiving grants, revenues from business incubators, and renting or selling vacant land.

Target Customer/Clients

The team drew the following conclusions about the customers and clients that the parks target after synthesizing the reports. On average, the parks target four separate clients/customers within their everyday operations.

Almost 90% of these parks have direct interest in science, technology areas. More than 27% out of those target multinational corporations (MNCs), established companies, and financial institutions as their primary clients. While large corporations are a primary target customer segment for these parks, many other parks also target smaller, private entities. In particular, over 16% of the parks target research institutes of some kind. Those customers may be private local and national research institutes, research foundations supported by Multi-National companies, and/or governmental research facilities. However, in some cases, these foundations and institutes engage in strategic partnerships with each other inside the ecosystem to create a symbiotic business model of mutual benefit. A full look at the various customer segments identified can be found in Figure 4.

Away from the established-business side of science and innovation parks's target customers, startups and business incubators are also very common clients. In fact, startups are the primary client in more than 19% of the parks, allowing them to leverage the plethora of opportunities, such as resources, funding, and connections, within the ecosystem. In addition to startups, 10% of the parks invite college students for seminars, information sessions and conferences pertaining to their field of study (life sciences, biotechnology, small scale manufacturing, etc). These parks also arrange educational courses and programs for various students in K-12 education and provide internships for College Graduates in STEM Courses.

In short, by far the three most common target customers among the parks researched were MNCs, research institutes, and startups, with a smattering of other, smaller target customers such as students and local learners. Some parks target universities, local businesses, and middle or high schools as customers, but those serve primarily as supplementary targets to the three mentioned above.

Value Proposition

Based on the reports, the team identified 65 different value propositions among the parks. Among those 65, there were many reasons that value would be created. Some parks are gain creators; they offer services such as rental space and other services that clients can use to their advantage. 92% of parks contained a value proposition regarding this rental space, by far the most common proposition. These offerings were framed in a contract-based lease and or membership for research hub purposes. Some are pain relievers; they offer incubator validation testing for research and startups to which they otherwise would not have access. 38% of parks have some kind of value proposition that falls under this category, which would allow startups and entrepreneurs to reach viability for future growth. Other value propositions include service dedicated to energy storage, connectivity, strategic governance partnership, and venture capital access. Most of the parks did not have a single value proposition, but had a few different propositions, but the majority had at least one of the two propositions mentioned above. A more thorough look into the various value propositions offered by all parks can be found in Table 7.

Based on the VT reports, current examples of science and innovation parks have a wide array of value propositions. Two are the most common - rental space/client services and incubator usage - but many parks offer other propositions that entice customers to come to the parks.

Conclusion

Broadly, the most common model that science and technology parks would be a park that operates as a nonprofit that targets MNCs, research institutes, or startups. The park would use rent, grants, and/or incubator programs for revenue streams to deliver on a value proposition of providing the space and resources necessary for a business to grow and conduct its operations. This is a general outline of the generic research park, but is also a good summary of the team's findings. The findings will guide the team as they continue into Phase Two of the consulting project. As discussed in the presentation on Thursday, this research will be paired with the research conducted on possible customer segments for the SWVEP to create a complete Business Model Canvas in the final presentation.

Appendix

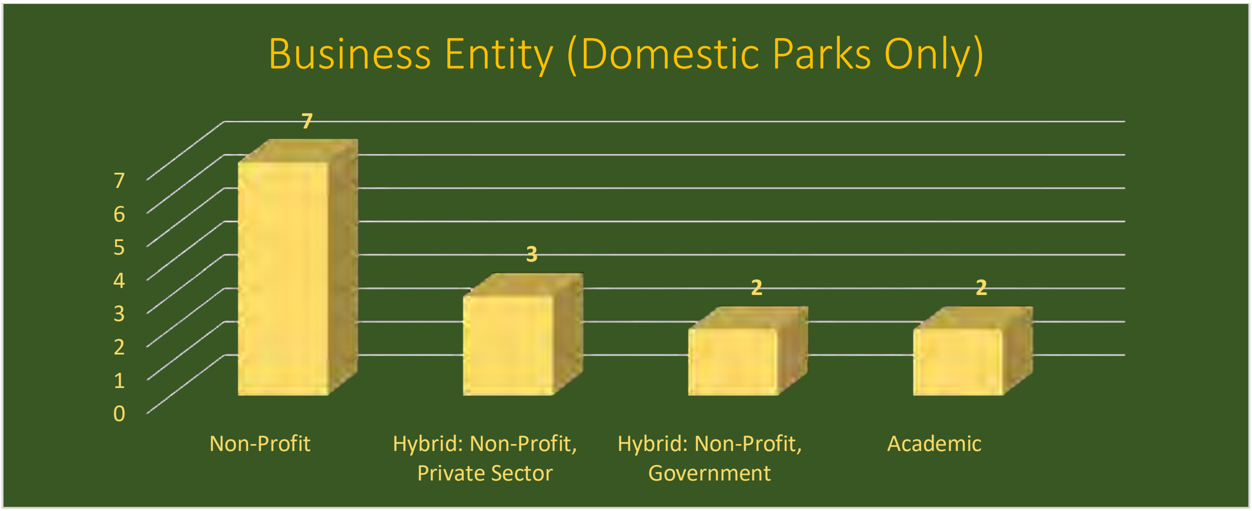

Figure 1. Business entities of 14 US-based research parks.

Table 1. Governance Structure.

Name	Location	Management Team	Board of Directors	Total	Entity
1717 Innovation Center (Startup Virginia)	Domestic	4	8	12	Hybrid: Non-Profit, Private
Central Florida Research Park	Domestic	6	0	6	Academic
Cummings Research Park	Domestic	1	7	8	Hybrid: Non-Profit, Private
Delaware Technology Park	Domestic	1	8	9	Non-Profit
Innovation Park	Domestic	7	13	20	Hybrid: Non-Profit, Government
Milwaukee County Research Park	Domestic	2	15	17	Non-Profit
National Cyber Research Park	Domestic	1	5	6	Non-Profit
Purdue Research Park	Domestic	14	16	30	Hybrid: Non-Profit, Private
Sanford Underground Research Facility (SURF)	Domestic	2	5,9	16	Hybrid: Non-Profit, Government
Rensselaer Tech Park	Domestic	1	0	1	Academic
Research Triangle Park	Domestic	4	50	54	Non-Profit
University City Science Center	Domestic	4	28	32	Non-Profit
Virginia Biotechnology Research Park	Domestic	5	10	15	Non-Profit
West Virginia Regional Tech Park	Domestic	6	4	10	Non-Profit
Amsterdam Science Park	International	6	-	6	Hybrid: Academic, Government
Berlin Adlershof	International		-		Hybrid
Cambridge Park	International	6	-	6	Hybrid: Private, Academic
Hsinchu Science Park	International		-		Government
Manchester Science Partnerships	International	7	-	7	Hybrid
PAKRI Science and Industrial Park	International	8	-	8	Hybrid
Qingdao Hi-Tech Zone	International	-	-		Government
Shanghai Zhangjiang Hi-Tech Park	International	-	-		Government
Waikato Innovation Park	International	-	-		Private
Zhongguancun Science Park	International	-	-		Government

Table 2. Partnerships.

Facility Name	**Partnership Information**
1717 Innovation Center	18 partners: 4 incubators/accelerators, 4 investor group, the local business chamber, 5 co-working spaces, 4 business development group Dominion energy innovation center: http://www.dominnovation.com/ SCORE: https://www.score.org/
Amsterdam Science Park	2 Main Partners: 1 University and 2 government organizations (University of Amsterdam, Municipality of Amsterdam, and Netherlands Organization for Scientific Research)
Berlin Adlershof	Robust network of partners, including IASP (International Association of Science Parks and Areas of Innovation)
Cambridge Park	2 primary partners- 1 university and 1 private
Central Florida Research Park	Primary Partnership w/ University of Central Florida
Cummings Research Park	Local County Chamber, Local Government
Delaware Technology Park	9 Partners listed- 1 national research institute, 2 technology forum, 1 sustainable chemistry group, SBDC, 1 University, 2 incubators, 1 government org
Hsinchu Science Park	Government - Ministry of Science and Technology
Innovation Park	Government - Leon County Research and Development Authority
Manchester Science Partnerships	Shareholders include Bruntwood SciTech, Manchester City Council, University of Manchester, Manchester Metropolitan University, Manchester University NHS Foundation Trust, Cheshire East Council, Salford City Council
Milwaukee County Research Park	9 Partners listed- 1 incubator, 5 business development groups (SBDC, Score), 1 Government, 2 Investment Group/Accelerator
University City Science Center	3 primary partnerships- 2 non-profit community partners and 1 university
Virginia Biotechnology Research Park	3 contributing partners - private sector, government, CPA 6 community partners

Figure 2. Revenue streams of 23 research parks.

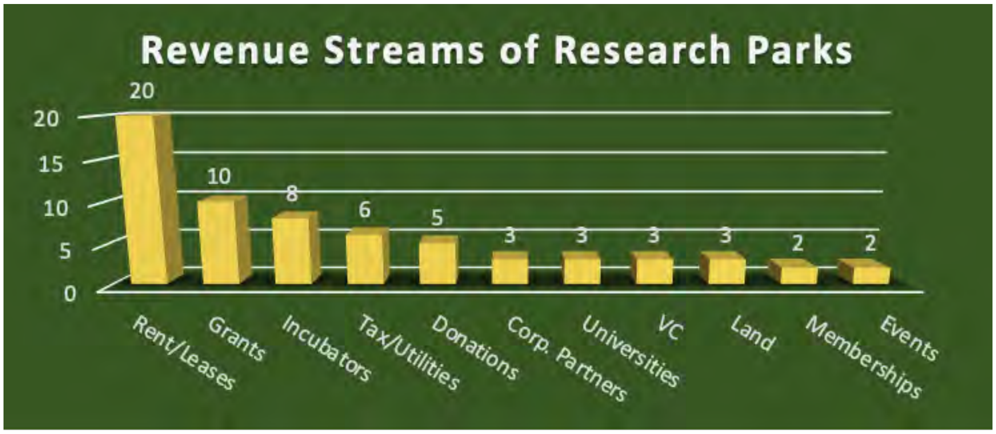

Figure 3. Revenue stream distribution.

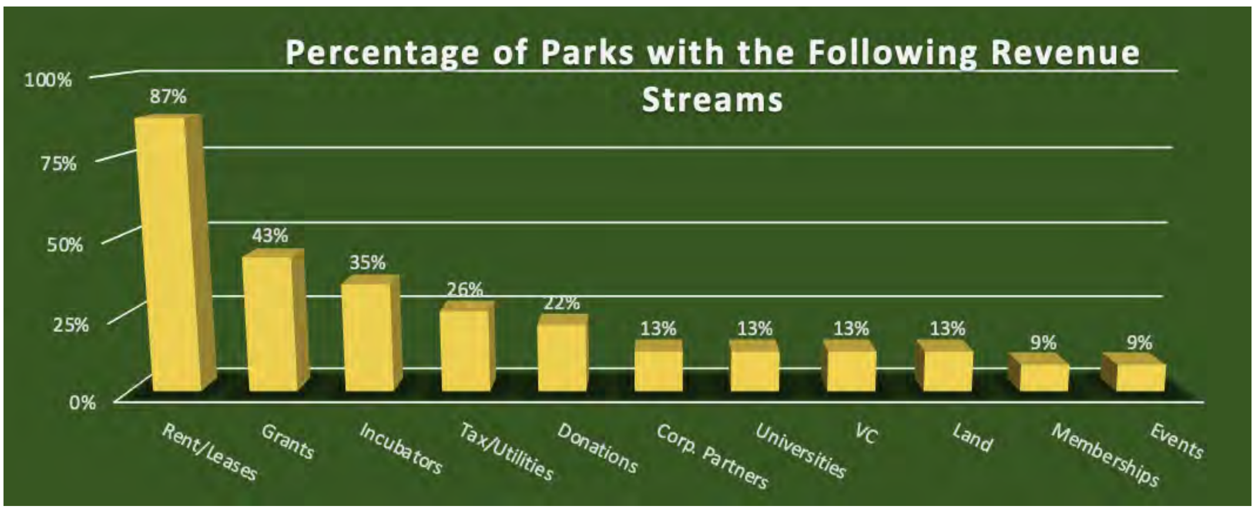

Table 3. Revenue stream information.

Facility Name	Revenue Stream Information
1717 Innovation Center	Multiple revenue streams: Idea factory where participants have to spend 13 hours a week for $500 flat fee Office space for rent for startups: $150 to $1600 a month depending on the size of the team renting Also supported by large corporate sponsor, Capital One
Amsterdam Science Park	Mainly university funding with companies in the park connected to the university in some capacity Also charge rent
Berlin Adlershof	Rent space by the square meter
Cambridge Park	Rent out labs to Cambridge affiliated research and startups Also have member companies
Central Florida Research Park	Get a lot of money from government military contracting Rent space based on activities being performed in the park: Office space, R&D, commercial space, hotels Also rent/sell vacant land Charge for utilities, water and sewage
Cummings Research Park	Rent and lease established spaces, also sell/lease vacant land Have four business incubators
Delaware Technology Park	Grants, incubator, and partnership with University of Delaware
Hsinchu Science Park	
Innovation Park	Rent and land development opportunities, offer seminars and classes across a range of topics for startups Incubator-type membership program Host an innovation pitch competition
Manchester Science Partnerships	Rent by the square foot, work with venture capitalists to fund some ventures
Milwaukee County Research Park	More residential aspect to it, have apartments and hotels for people to live in Rent office, lab, and light manufacturing spaces by the square foot Use grants
National Cyber Research Park	Significant local and federal government investments Grants
PAKRI Science and Industrial Park	Rent space, also have equity agreements with some startups developed in the park Crowdfunding, partnership with an incubator Rent out space to use the resources at the park

Table 3. continued

Purdue Research Park	Primarily use university funding to operate the park
Qingdao Hi-Tech Zone	Make revenues from taxing the tenants, almost like a faux-district in China Charge 5-10% on revenues from patents Have a sole proprietorship to invest in good programs
Sanford Underground Research Facility (SURF)	Major government funding/grants, private donations, and corporate partnerships
Shanghai Zhangjiang Hi-Tech Park	Taxes and rent, similar to Qingdao
Rensselaer Tech Park	Private donations, space and land leases
Research Triangle Park	Primarily rent and land leases
University City Science Center	"Program Services" and donations
Virginia Biotechnology Research Park	Leasing and grants Have memberships for startups and entrepreneurs, and partner with an incubator
Waikato Innovation Park	Rent office space and conference room space
West Virginia Regional Tech Park	Rent, utilities, offices and labs for lease Donations
Zhongguancun Science Park	Rent, grants, taxes Entice people to come to the park through discounted tax and utilities costs

Table 4. Target Clients.

Facility Name	Target Clients
1717 Innovation Center	Startups
Amsterdam Science Park	Startups, MNCs, Research Institutes, Non-Profits
Berlin Adlershof	Startups, College Students, MNCs, Local Businesses
Cambridge Park	MNCs, College Students
Central Florida Research Park	Local Businesses, Manufacturing companies
Cummings Research Park	MNCs, High-tech enterprises, Government agencies, Business Incubators, College Students, Research Institutes
Delaware Technology Park	MNCs, Startups, Research Institutes, Business Incubators
Hsinchu Science Park	High- Tech companies, Scholars, Small scale enterprises, Research institutes
Innovation Park	University Research Facilities, Manufacturing Companies, State/federal research facilities
Manchester Science Partnerships	Startups, Venture Capital Firms, College Students
Milwaukee County Research Park	Technology-based companies, Medical Centers, Universities, Startups, Manufacturing Enterprises
National Cyber Research Park	MNCs, Research Institutes, K-12 Schools, College Students
PAKRI Science and Industrial Park	Greentech Startups, Crowdfunding resources, Real Estate Partners, MNCs
Purdue Research Park	Research foundations, Incubators, MNCs, Research institutes
Qingdao High-Tech Industrial Development Zone	Financial Institutions, Startups, Establishes Companies, Universities and Schools
Rensselaer Technology Park	Established companies
Research Triangle Park	Startups, MNCs, College Students
Sanford Underground Research Facility	K-12 Schools, Tourists, College Students, Research Institutes, Research Foundations
Shanghai Zhangjiang Hi-Tech Park	Established companies, MNCs
University City Science Center	Startups
Virginia Bio Technology Park	Government agencies, MNCs, Startups, Research Institutes
Waikato Innovation Park	Startups, Established Companies
West Virginia Regional Technology Park	Research Institutes, Established Companies
Zhongguancun Science Park	MNCs, Research Institutes, Establishes Companies, High-tech Enterprises

Figure 4. Distribution of customer segments.

Table 5. Value Proposition Information.

Facility Name	Value Proposition Information
1717 Innovation Center	• Gain Creators: design lab, conference venue and event space for the Richmond community, hyper-focused on start-ups • Pain Relievers: one single place where community leaders and entrepreneurs can engage planning, investment, environmental protection and safety, business, construction management and land development • Products & Services: Capital One resources, $150 million "Future Edge" program, design lab, event space, conference center
Amsterdam Science Park	Amsterdam Science Park • Gain Creators: beta center, university focused, research center, scientific startups are welcomed, • Pain Relievers: connects companies with R&D expertise, has a directory of collaborators to partner with, • Products & Services: research hub, office space
Berlin Adlershof	Berlin Adlershof Science City • Gain Creators: multi-city connections in Germany • Pain Relievers: all sectors of design occur here • Products & Services: office space, incubator
Cambridge Park	Cambridge Science Park • Gain Creators: company and office space capabilities, lots of capital, nice mix of startup and well-established companies, office space, strong brand success in Europe, over 7520 employees, • Pain Relievers: lots of facilities space for new companies, Nursery, very lifestyle focused • Products & Services: technology and life science office space, scientific research, and development office space, "ParkLife"
Central Florida Research Park	• Gain Creators: "university-based relationships", land purchasing availability, office space leasing options, lab manufacturing usage, creates accessibility for customers, relationship building opportunity with University of Central Florida • Pain Relievers: employee benefits, university resources • Products & Services: technology transfer, research, faculty consultations, computer database access
Cummings Research Park	• Gain Creators: second largest research park in the country and the fourth largest in the world, 300 companies, more than 26,000 employees and 13,500 student, major capital , future focused research park, event focuses, treats employees well , longevity, • Pain Relievers: large company space • Products & Services: huge office space

Table 5. continued

Delaware Technology Park	• Gain Creators: "leading East-Coast" non-profit research park (reputation), job creation, university ties with The University of Delaware, strategic alliances, • Pain Relievers: a regional hub for technology innovation, space for tenants, access to state-wide connections, both academia and private. • Products & Services: Incubation space, laboratory space, over 31 resident innovators to collaborate with, five different campuses, small business focus
Hsinchu Science Park	• Gain Creators: 6 different parks, world renowned, unlimited resources, and capital, over 20 major companies have residences at the park (Apple, Logitech, Philips, Realtek), worlds first science park • Pain Relievers: capital inflows in excess of NT$4 trillion, human resources management, ventures management • Products & Services: vast network of services, this is one of the most diversified companies out of this group
Innovation Park (Tallahassee)	• Gain Creators: working in affiliation with Florida State University, Florida A&M University, and Tallahassee Community College, City, County, and private sector leaders to promote our region's research and development assets, • Pain Relievers: advanced research facilities • Products & Services: office space and incubator, TechGrant program
Manchester Science Partnerships	• Gain Creators: strategic public, private, academic, clinical partnership, innovation office space center, incubator space • Pain Relievers: powerful shareholders, health focused • Products & Services: "Citylabs", Manchester Science Center,
Milwaukee County Research Park	• Gain Creators: office space, incubator space, history of successfully completed projects (i.e., Mayfair Woods Business & Technology Center, Oakwood Center) • Pain Relievers: collaborative company connections, medical center with GE research park, campus connections, biosciences focus • Products & Services: wet laboratory innovation space, office, and IT space,
University City Science Center	• Gain Creators: urban centered in Philly, office and incubator space, longevity (since 1963), • Pain Relievers: over 31 shareholders, very collaborative environment, supports local Philly jobs • Products & Services: venture focused, incubator space, office space, event space, "FirstHand" – program for students to engage with the park, QED university program

Table 5. continued

Virginia Biotechnology Research Park	• Gain Creators: Richmond focused, connected with VCU, private and non-profit companies, state and federal laboratories, and research institutes/administrative functions of VCU and VCU Health • Pain Relievers: State backed • Products & Services: office and incubator space, looks like some of the best in VA
National Cyber Research Park	• Gain Creators: non-profit base, rooted in research, government relations and academic focus, strategic partnership alignment • Pain Relievers: median for government needs and private ventures in Louisiana, internship and job focused for STEM based opportunities, Bossier Parish Community College opportunities for students • Products & Services: Air Force collaboration, ecosystem of over 7 major Louisiana state university, event planning
Qingdao High-tech Industrial Development Zone	• Gain Creators: creative hub for communication and transportation systems • Pain Relievers: N/A • Products & Services: public technology
PAKRI Science and Industrial Park	• Gain Creators: large workforce, huge landmass, city focused, entrepreneurial rooted, 200+ companies operating in park • Pain Relievers: closed electricity distribution ability, renewable energy, 5 active science R&D centers, 25+ startup companies in Startup Incubator • Products & Services: business incubation, consultation, focused on Estonian partnerships, office space,
Purdue Research Park	• Gain Creators: major player in commercialization and economic development in Indiana, discovery park district, over seven park locations, • Pain Relievers: world class research capability and university resources, faculty access • Products & Services: office and incubator space, property development, scientific labs
Rensselaer Technology Park	• Gain Creators: America's first technological research university (reputation), incubator testing, office space, university connected, flex spaces, design lab partnerships, • Pain Relievers: fully staffed, office spaces, event planning and event space • Products & Services: several facilities used to help 5 types of companies thrive (Biotech/life science, computational science and engineering, nanotechnology and advanced materials, energy smart systems, media arts)

Table 5. continued

Research Triangle Park (Research Triangle Park, NC)	• Gain Creators: university focused with major NC public and private universities, 7,000-acre campus, • Pain Relievers: urban development • Products & Services: office space, retail space, hotel, and green space
Sanford Underground Research Facility (SURF)	• Gain Creators: Super heavy on physics and the science foundation of companies, multidisciplinary research rooted, research facility, South Dakota space, multiple campuses • Pain Relievers: University ties with Black Hills State University, heavy community outreach component • Products & Services: research center, K-12 leadership for students, online resources for educators,
Shanghai Zhangjiang Hi-tech Park	• Gain Creators: highly connected network of over 24,000 companies, more than 150 national and municipal R&D institutions. Over 20 buildings they own. • Pain Relievers: Investment component, helps start up companies receive funding and support, loan incubator • Products & Services: professional real estate and consulting services
Waikato Innovation Park	• Gain Creators: 60+ business residences, adaptive office space, laboratory suites, connectivity • Pain Relievers: agrotechnology, the environment, information technology expertise • Products & Services: tenant space
West Virginia Regional Technology Park	• Gain Creators: research technology park, 4 current tenants, • Pain Relievers: new entrant, like Coalfield, hyper focused on serving the West Virginia community, • Products & Services: office and research space, training facility space, processing lab space
Zhongguancun Science Park	• Gain Creators: over ten parks, innovation hub • Pain Relievers: incubator for Chinese companies in Beijing “hi-tech” • Products & Services: office / incubator space

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KC Malone

Ekansh Mittal

Max Baldwin

Cara Simpson

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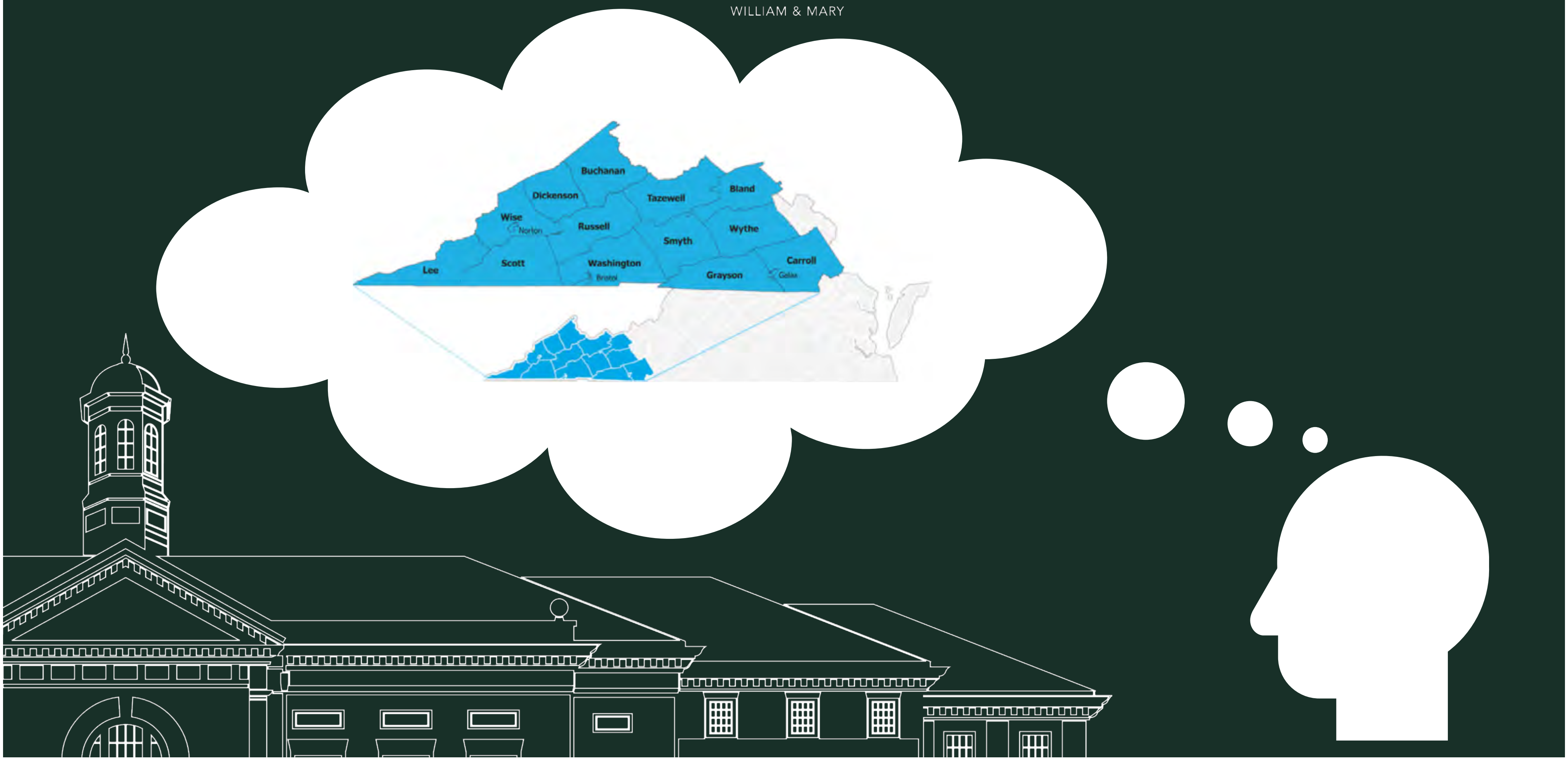

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Virginia
Southwest
strategic
InvestSWVA
development
economic
private
region
prospect
business
location
well
relationships
investment
energy
industry
including
sustainability
leadership
strategies
advantages
focused
disruption
public
team
high-tech
Significant
Senator
partners
Delegate
efforts
drive
builds
leading
vision
future
idea
offers
work
like
big
new

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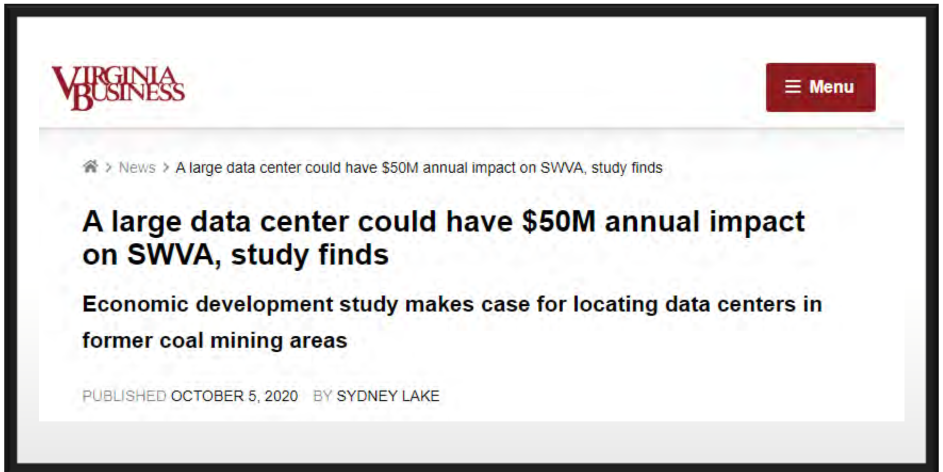
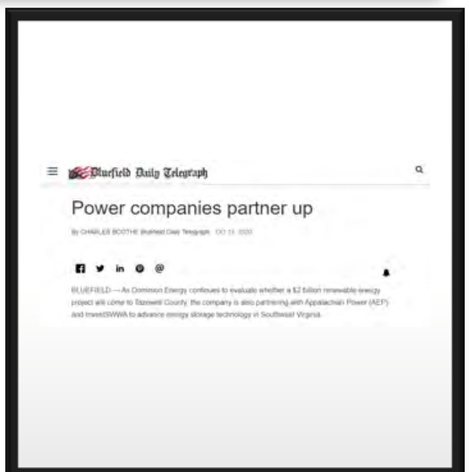
Agenda

- Introduction to Southwest Virginia
- The Opportunity
- Our Process
- Roadmap to Success
- Conclusion (Q/A)


VIRGINIA BUSINESS
Menu
News > A large data center could have $50M annual impact on SWVA, study finds
A large data center could have $50M annual impact on SWVA, study finds
Economic development study makes case for locating data centers in former coal mining areas
PUBLISHED OCTOBER 5, 2020 BY SYDNEY LAKE


BRISTOL HERALD COURIER
'IT'S COMMITTED TO ADVANCING BIG IDEAS'
InvestSWVA


Bluefield Daily Telegraph
Power companies partner up


INVEST SWVA
Opportunity Awaits in Southwest Virginia
Home About Projects
News
Nov 12
SPIG Industry expands Southwest Virginia operations with 113 jobs and $7.9 million investment
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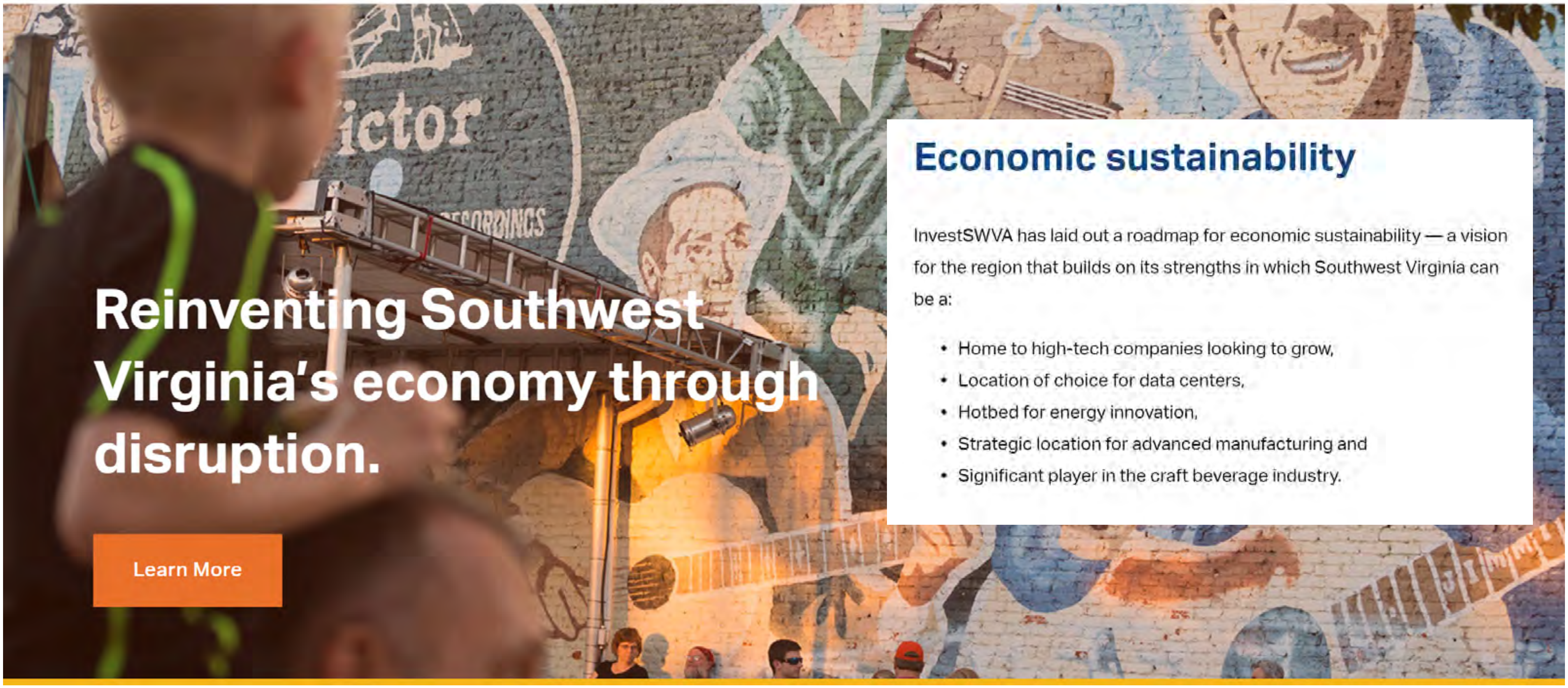
INVEST SWVA

Opportunity Awaits in Southwest Virginia



Reinventing Southwest Virginia's economy through disruption.

Learn More

Economic sustainability

InvestSWVA has laid out a roadmap for economic sustainability — a vision for the region that builds on its strengths in which Southwest Virginia can be a:

- Home to high-tech companies looking to grow,
- Location of choice for data centers,
- Hotbed for energy innovation,
- Strategic location for advanced manufacturing and
- Significant player in the craft beverage industry.

The Vision

Southwest Virginia as a:

hotbed for energy innovation

&

home to high-tech companies looking to grow

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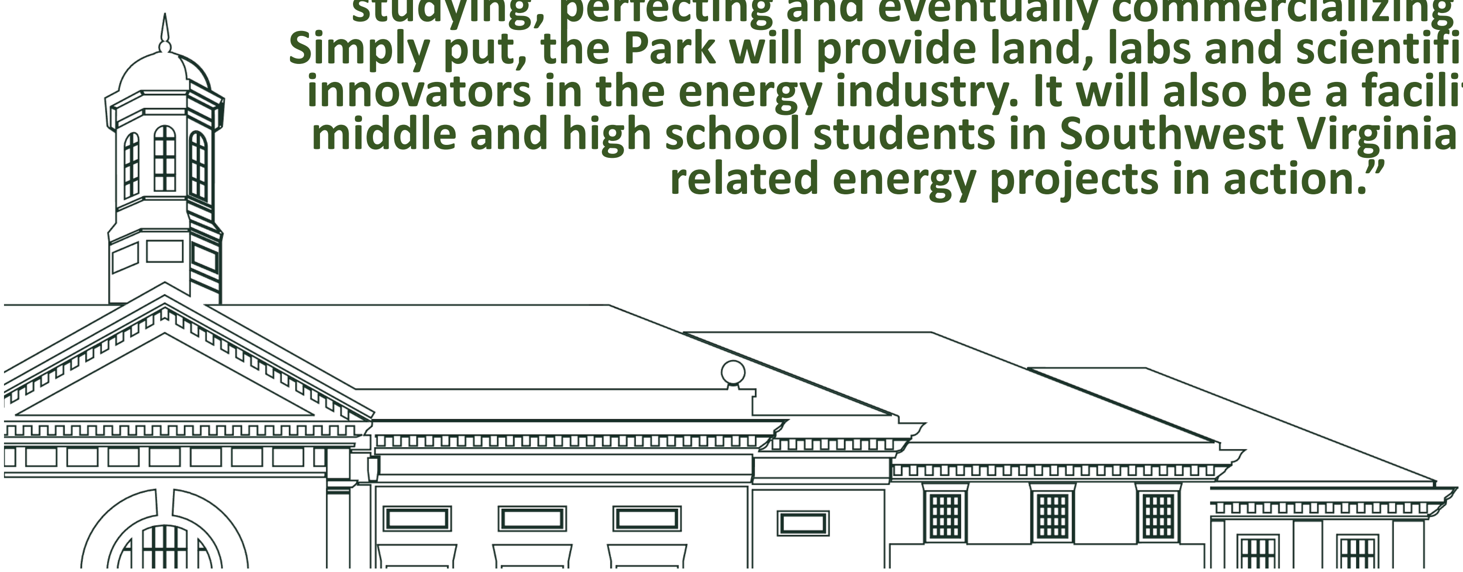
Project Innovation

"The Southwest Virginia Energy Research Park will be a first-of-its-kind operation in the United States and will host companies interested in studying, perfecting and eventually commercializing their ideas. Simply put, the Park will provide land, labs and scientific assistance to innovators in the energy industry. It will also be a facility that allows middle and high school students in Southwest Virginia to see STEM-related energy projects in action."



The Opportunity

Sustainability

- Carbon Reduction Goals
- Climate change/carbon-top ESG criterion for investors

Portfolio Modernization

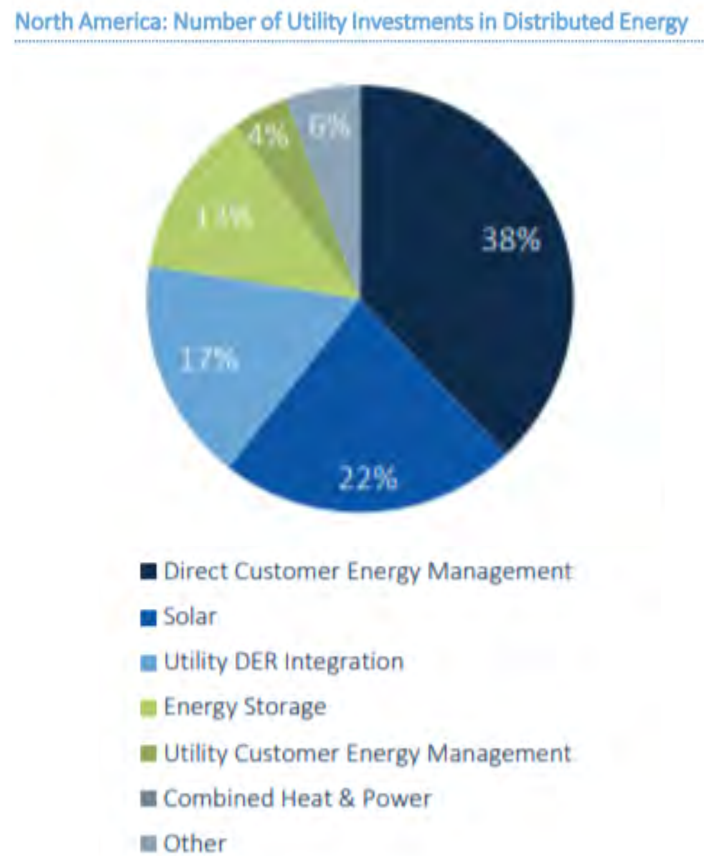
- Changing customers' needs
- Distributed Energy Resources systems

Business Model Transformation

- New tech, evolving customer preferences, changing customer landscape
- Exploring transactive energy models

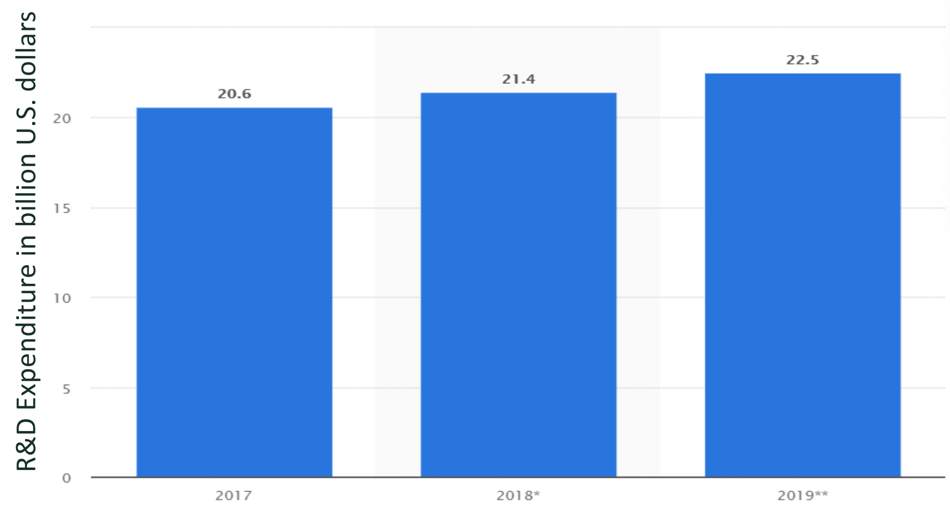
Core Growth

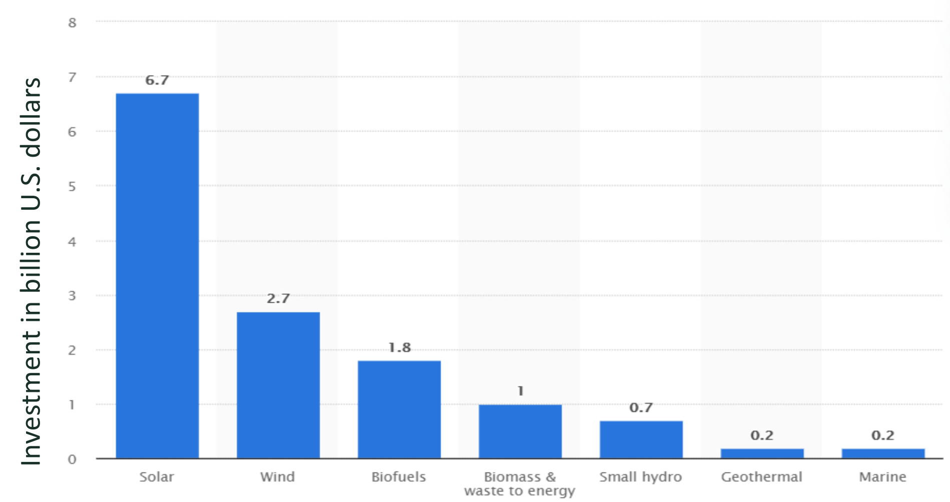
- Smart cities projects
- Utilities as a foundational player



The Opportunity

- 8% increase YOY in R&D Spending in United States
- Solar and Wind saw the biggest investments.
- Currently, $2.3 Trillion dollars in assets by clean energy investors.





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Our Process

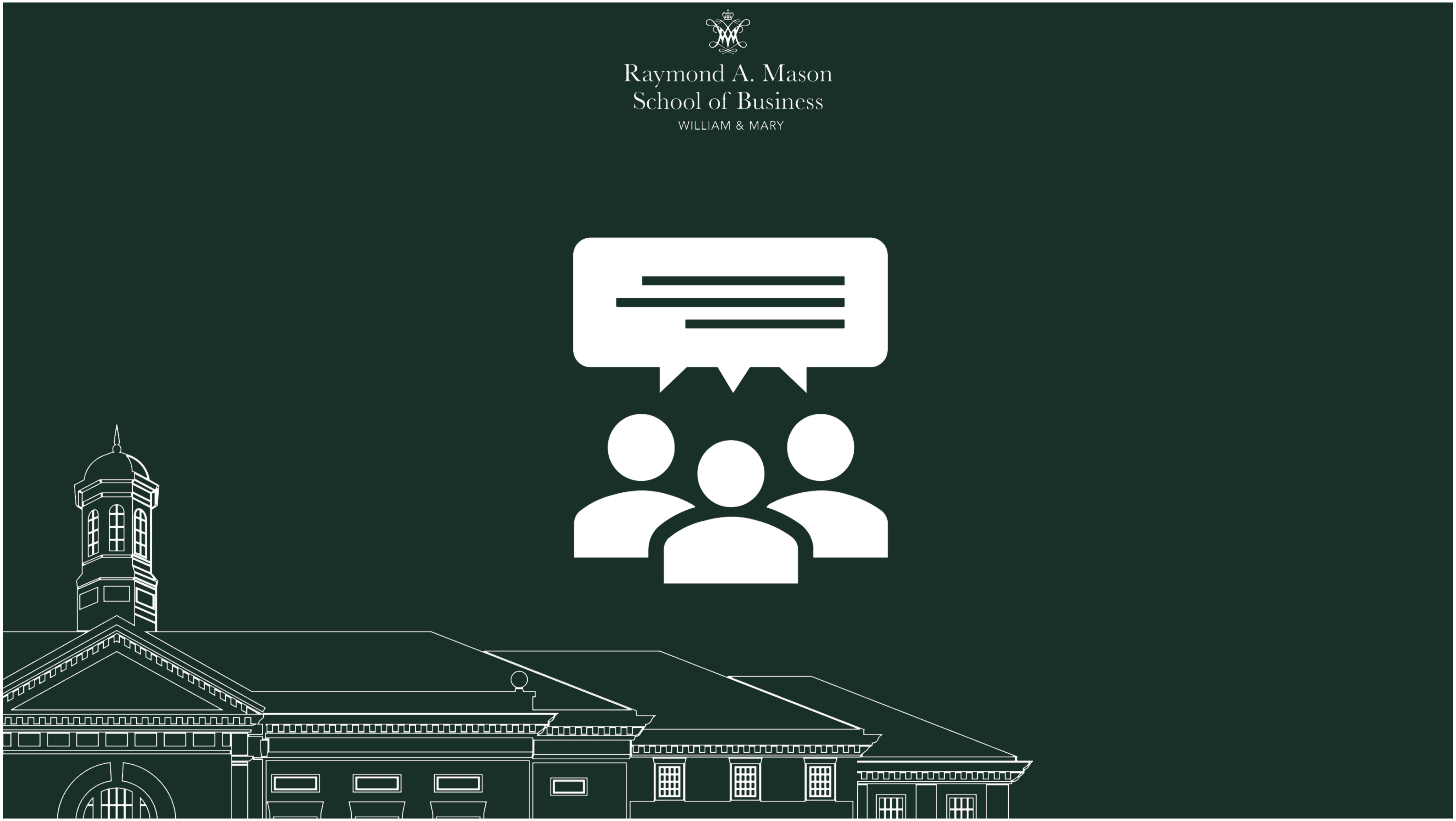
CREATED A DRAFT OF A BUSINESS MODEL FOR PROJECT INNOVATION

IDENTIFIED CRITICAL ASSUMPTIONS IN THE MODEL

CONDUCTED INTERVIEWS WITH 6 INDUSTRY EXPERTS & A SURVEY TO VCS

SOUGHT OUT ADDITIONAL RESOURCES

UPDATED THE BUSINESS MODEL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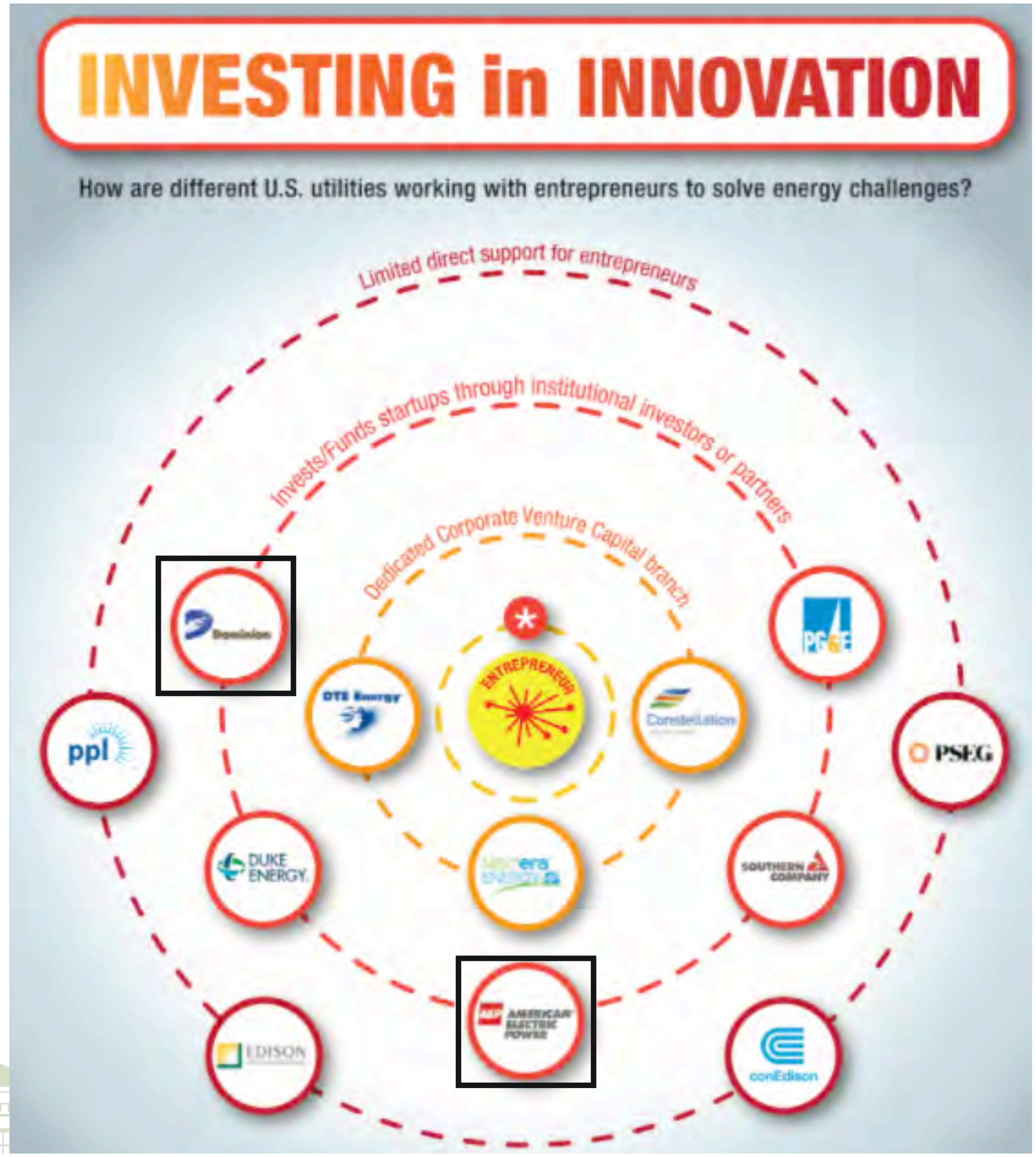
Roadmap to success

- Know your target customer
- Understand their needs
- Build strong partnerships
- Foster collaboration
- Be customer-centric
- Invest in providing value
- Embrace the community
- Leverage your strengths
- Start small and build

Know your target customer

Energy Companies

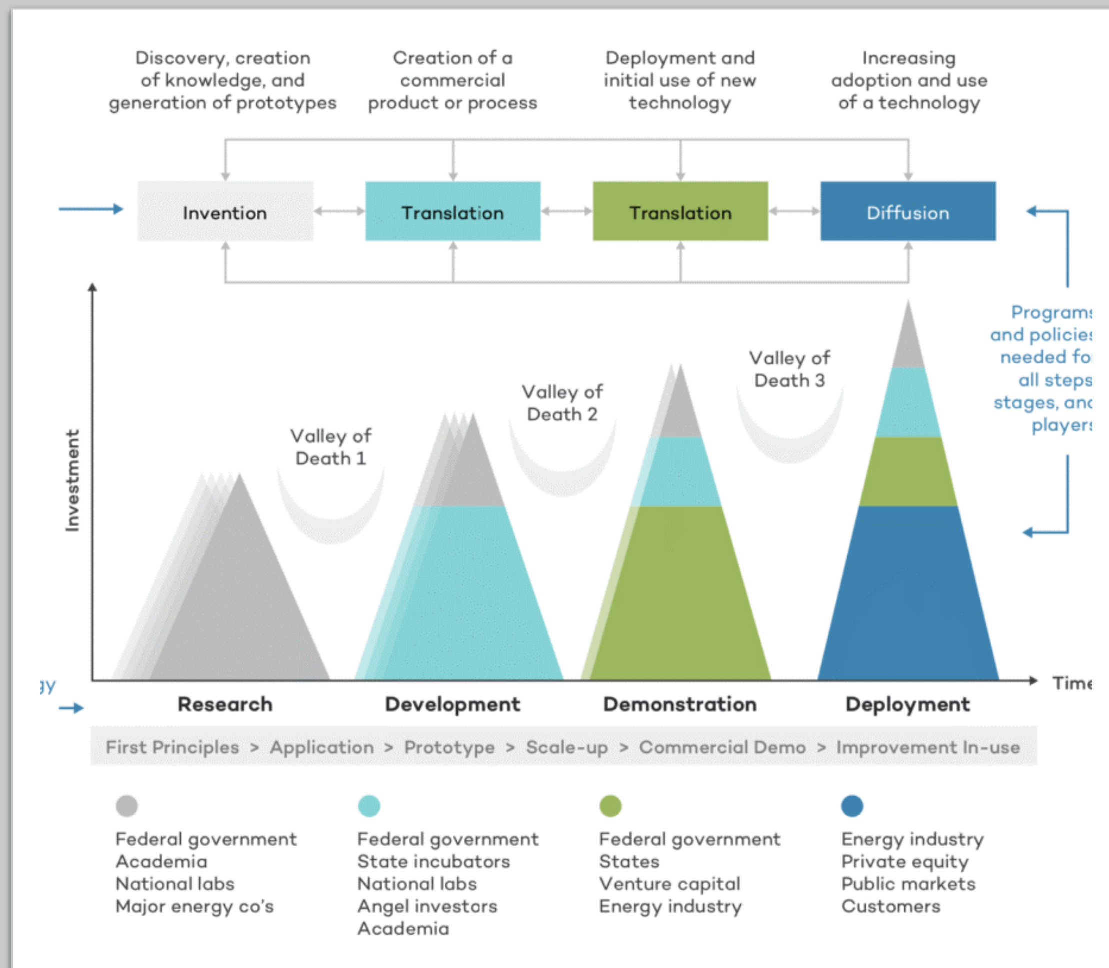
- Service areas in Virginia, Tennessee, West Virginia, and North Carolina
- Strong interest in energy innovation & renewables



Know your target customer

Mid- to Late-Stage Startups

- Renewable Energy or Cleantech Focus
- Hardware-oriented
- Commercial potential



16 | Corporate Field Consultancy - Fall 2020

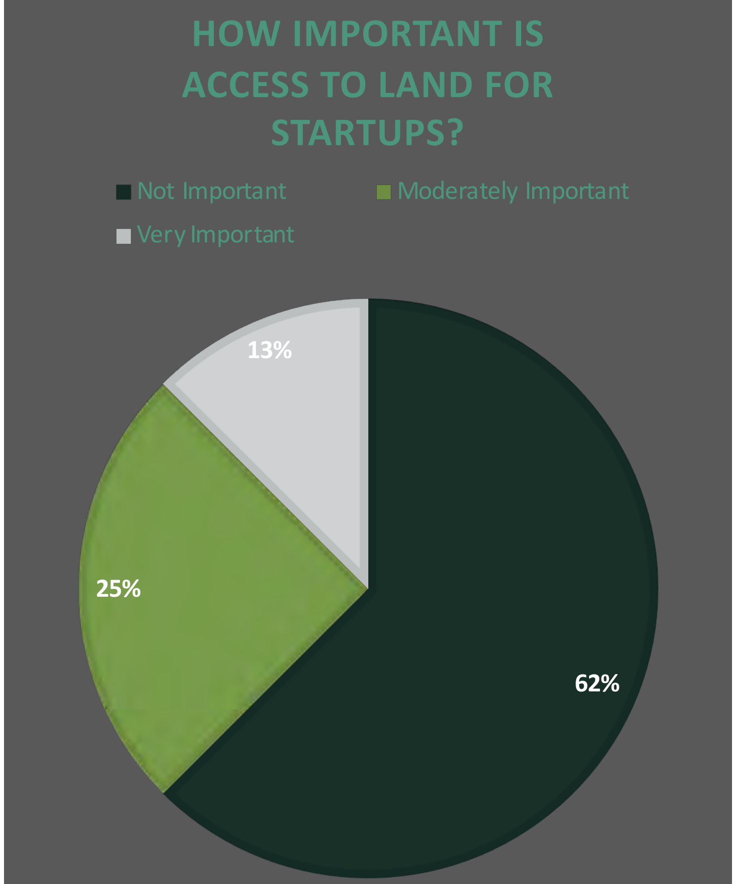
Energy companies:

- Land – and a lot of it
- New ideas & technology
- PR help

Startups, more than land, need access to:

- Capital
- Customers
- Commercialization
- Other business development tools
- Dependable internet connection for rural entrepreneurs

Understand their needs



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Build strong partnerships

Regional connections

- Local government

Strategic networks

- Venture capital firms
- Government Groups – DMME
- Research institutions

Foster collaboration

Critical for startups

- Need opportunities to learn from one another
- Shared spaces for work and leisure
- Events focused on networking and relationship building

Mutual benefit between customer segments

- Novel ideas
- Investment opportunities
- Customer discovery

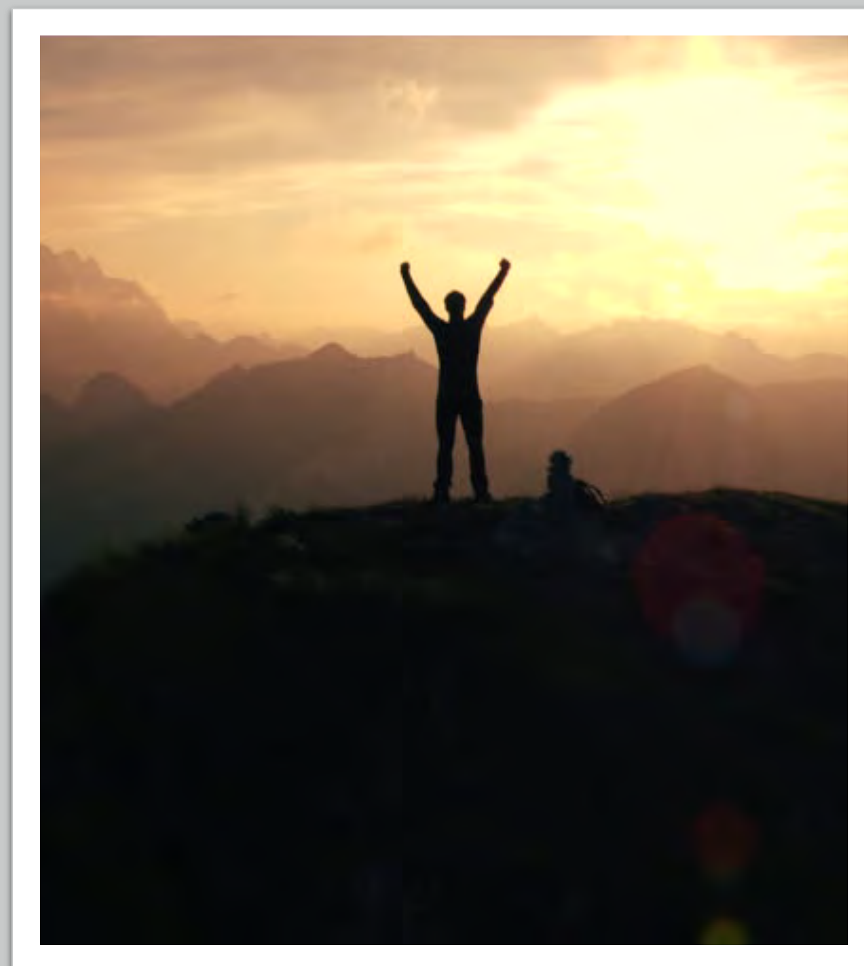
Be customer-centric

Entrepreneurs are the heart of innovation

- Portfolio of services to help them survive

BUT, must have models for both segments

- Longer-term land leases for energy companies
  - 2 year minimum
- Membership plan for entrepreneurs/startups
  - 6- to 12-month memberships
  - Different tiers
    - Land Usage (time or acreage)
    - Simpler access to network/resources



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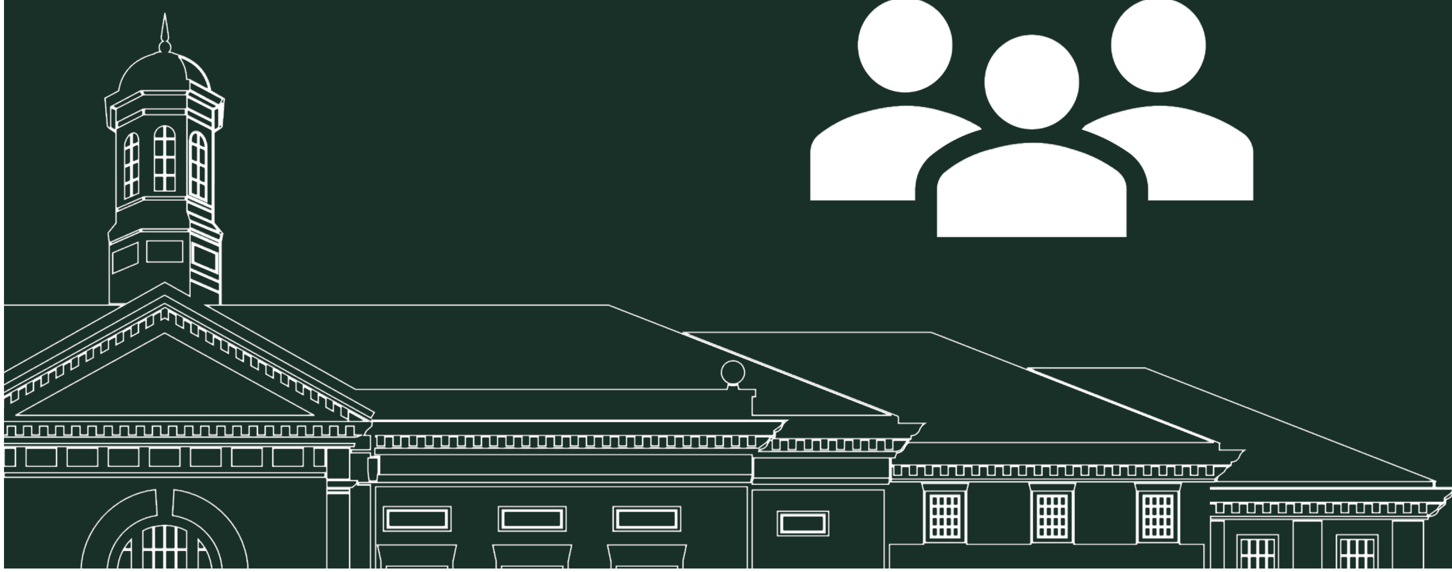


Invest in providing value

Create community

- Shared space and quality services

Events & Activities

- Attended by energy company employees, startups, local partners, investor groups, and industry experts

Startups are often heavily subsidized

- They are the source of community and innovation

Embrace the community

Celebrate town heritage

- Lessons from Big Coal

Events focused on education and community building

- Helps the park, but also the park's primary customers

Job creation and economic opportunity

Leverage your strengths

Land availability

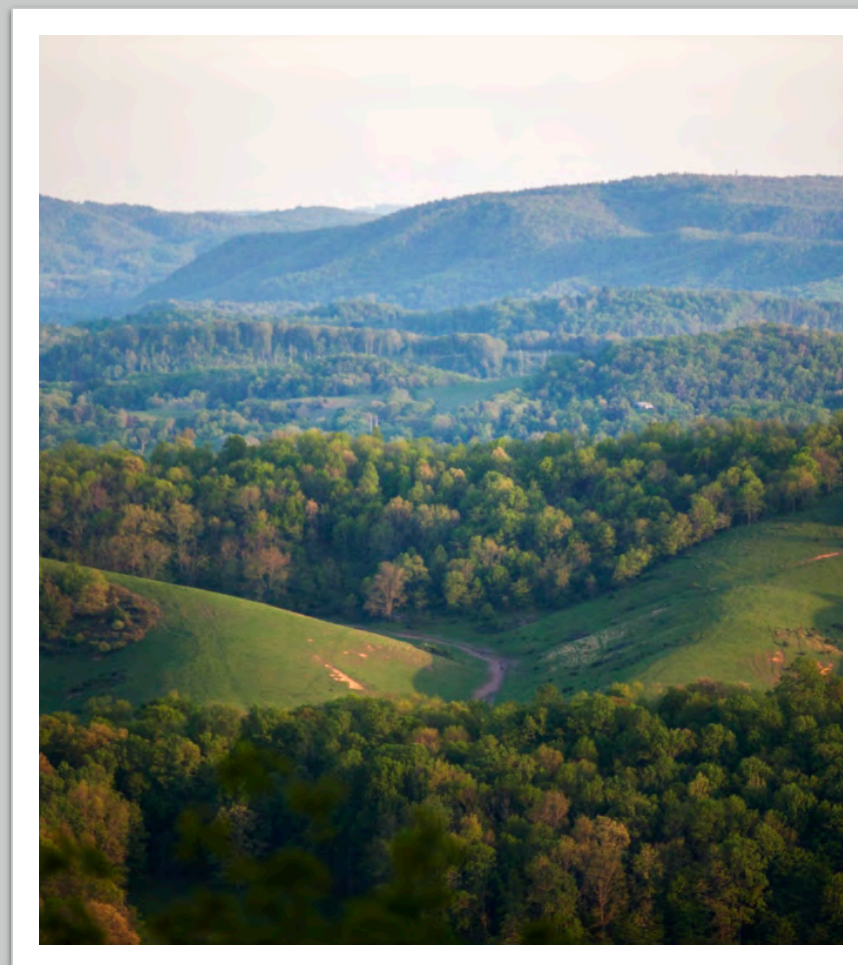
- Diverse terrain, mineral, & underground resources

Local knowledge base

- Political connections
- Understanding of the region

Potential as a disruptor AND a connector

- Creating a network diverse stakeholder interests



Start small and build

Business entity recommendation:

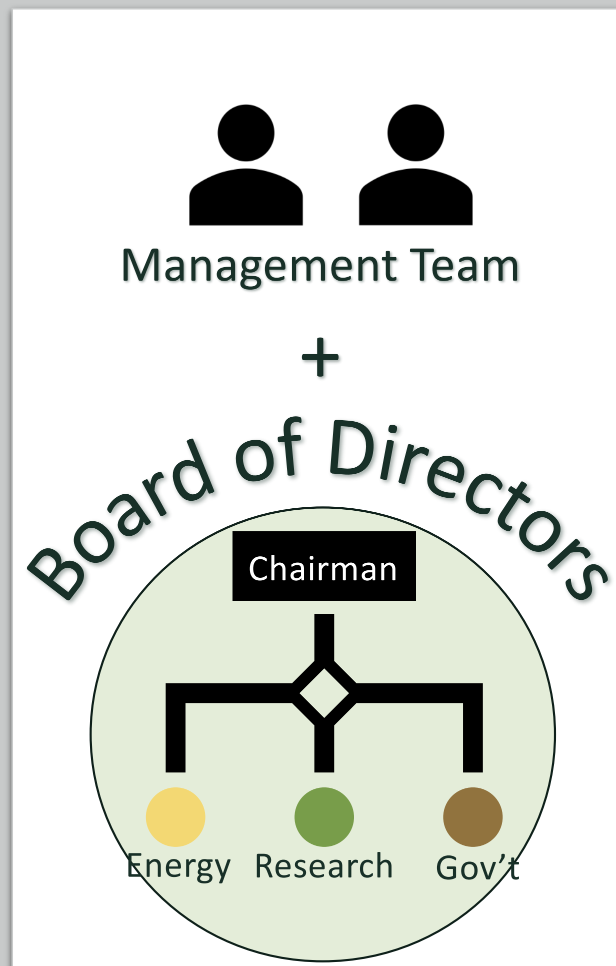
- 501c3 non-profit corporation

Small, agile board of directors & management team

- Board of directors to offer advice and strategy: experience in business development, energy sector, grant writing, government
- Management team for the day to day

Down the road there are options:

- Growth
- Authority boards
- Additional business entities (LLCs)



Roadmap to success

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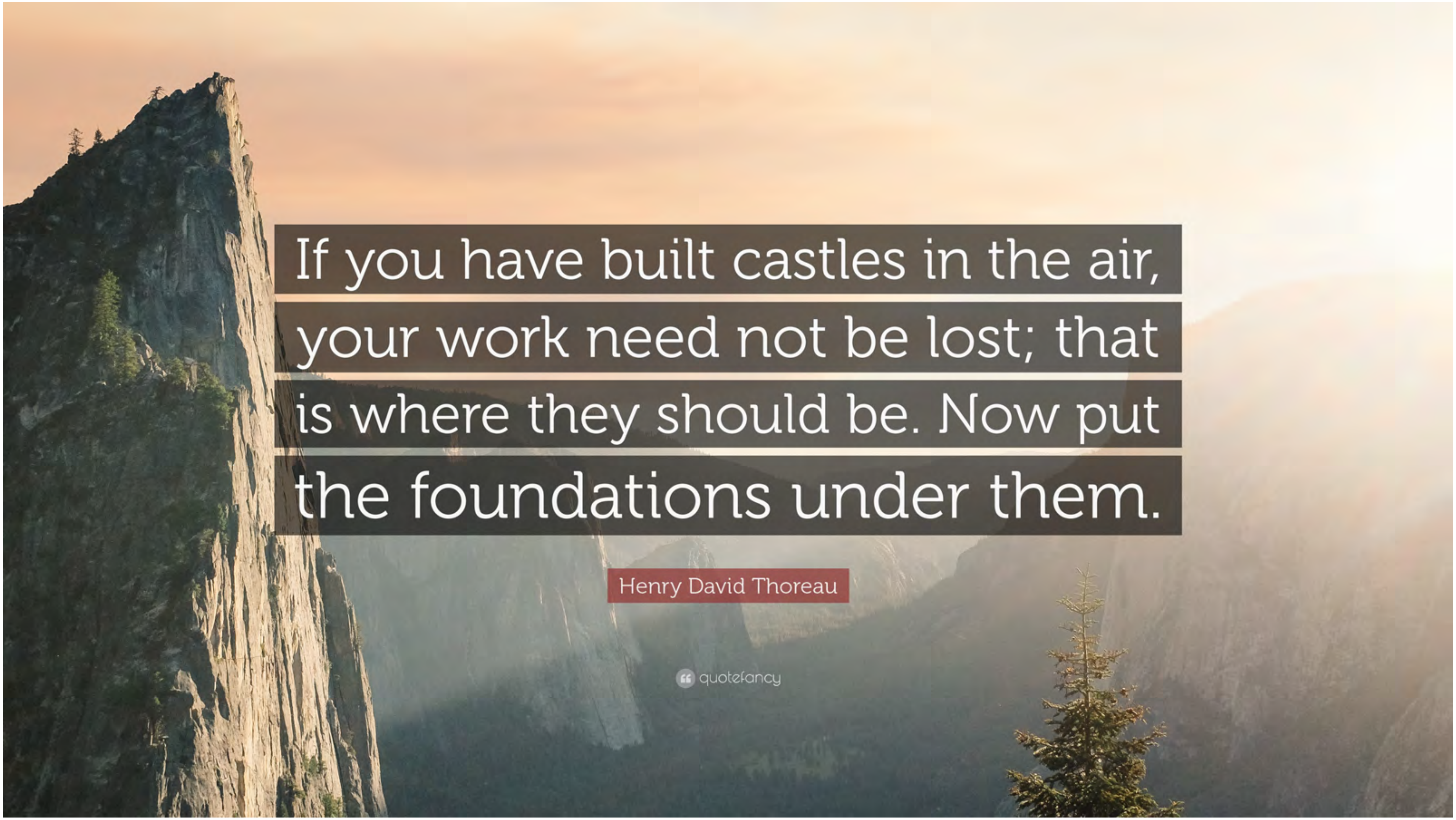
If you have built castles in the air,
your work need not be lost; that
is where they should be. Now put
the foundations under them.
Henry David Thoreau
quotefancy

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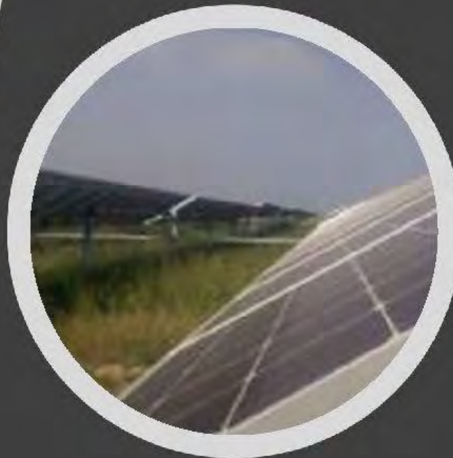
Thank you!

Final Report - Location Vetting for Southwest Virginia Energy Research Park

September 2021

Prepared for:
LENOWISCO Planning District Commission
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Duffield, Virginia 24244

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September 3, 2021

Mr. Jimmy Adkins
Director of Planning
LENOWISCO Planning District Commission
372 Technology Trail Lane, Suite 101
Duffield, VA 24244
(276) 431 2206

Subject: Final Report - Location Vetting for Southwest Virginia Energy Research Park

Dear Jimmy:

Marshall Miller & Associates, Inc. (*MM&A*) is pleased to provide the following report to **LENOWISCO Planning District Commission *(LENOWISCO)*** pertaining to location vetting for an Energy Research Park in Southwest Virginia. MM&A's project team for this assignment included **HDR, Inc. (*HDR*)** and **Thompson & Litton (*T&L*)**. This was an exciting project for us, and we look forward to working with you in the future to further develop this project and others like it.

Should you have any questions on the attached proposal, please do not hesitate to reach out to us directly.

Sincerely,
MARSHALL MILLER & ASSOCIATES, INC.

Steven A. Keim, PhD, PE	Kevin M. Andrews, CPG
Sr. Vice President	Vice President
Direct Line: 1 540 605 9004	Phone (+1) 276-970-6065
Email: steve.keim@mma1.com	Email: kevin.andrews@mma1.com

/rgw
Attachments
File: Final Location Vetting for SW VA Energy Research Park (LEN100, 2021-09-03).docx

Table of Contents

TABLES

FIGURES

Attachments

1 Introduction

Project Innovation, a proposed energy park in Southwestern Virginia (herein referred to as the "***Energy Park***"), represents a unique approach to leverage the region's assets by ultimately constructing a facility capable of demonstrating various energy technologies and providing a means to conduct energy-based research at the field scale. The Energy Park facility is intended to impact the future path, growth potential, and eventual transformation of Southwest Virginia.

LENOWISCO Planning District Commission *(LENOWISCO)* engaged the Marshall Miller & Associates project team to conduct vetting of various potential locations for the Energy Park. The location vetting project was jointly funded by a **GO Virginia** grant and the **U.S. Economic Development Administration**.

The concept of development for the Energy Park is "Smart Energy", meaning energy that is affordable, dependable, reliable, secure, diverse, and clean. Smart Energy uses transformational technologies to encourage economic development, promote independence, and support circular economy goals. The use of Smart Energy supports a transition to the "digital" operations of energy plants and facilities. The overall motivation of the project is to create a unique facility that promotes education, research and demonstration, and community outreach.

The location vetting process considered numerous potential sites, realizing that the development of the Energy Park concept will likely be an incremental building process that will take place over a period of time. Likewise, while the Energy Park may have a "main" facility, it is likely that satellite facilities will develop as a result of site availability and capability. For these reasons, it is important that the Energy Park development team is flexible and that the overall plan is easily adaptable to realize opportunities as they are presented.

The Energy Park concept focuses on the following key research areas:

1. **Electricity Generation** – Generation of electricity, or Smart Energy, should be green, affordable, and diverse. Electric generation technologies also include energy storage, such as battery installations or pumped storage hydropower (PSH) technology. Preferable sources of energy include solar, wind, and BioEnergy, and even High Efficiency Low Emissions (*HELE*) coal plants.
2. **GeoEnergy** – GeoEnergy, or energy from the Earth, includes concepts such as geothermal energy production and eco-friendly coal or natural gas energy production. GeoEnergy provides security, sustainability, and independence.
3. **Going Digital** – Going Digital refers to using strategies to make our energy generation and delivery systems and facilities more efficient. The technology includes sensors, controls, autonomous

machines, and even machine learning and human-machine interactions. The Energy Park concept includes the potential to house facilities that would serve to test and develop such technologies.

4. **Circular Economy** – The concept of circular economy promotes sustainability, responsibility, and entrepreneurship to develop and improve methodologies for reusing materials and finding alternative uses for existing materials. This concept includes evaluation of options for end-of-life strategies for renewable generation components and the remains of the fossil fuel industry in Southwest Virginia and beyond.

5. **Supporting Facilities** – Existing facilities to support the development of the Energy Park concept are abundant in Southwest Virginia and other similar areas. The existing facilities include previously mined areas, including both reclaimed and Abandoned Mine Land (*AML*) features. AML features may include waste dumps, old surface infrastructure, impoundments, depleted gas wells, decommissioned power plants, and others. Both existing surface and underground mines present various opportunities for development of Energy Park concepts. Examples include use of water from inundated underground mines for PSH and geothermal cooling purposes, to use of abandoned surface mine areas for development of new surface facilities on flat ground. New facilities to be constructed as the Energy Park concept develops are expected to be consistent with the previously described key components, and flexible enough to allow for various opportunities as they arise. For example, the Energy Park concept may begin as a site for battery storage which necessitates a purpose-built structure to house the batteries and development of basic site access. Further development may include opportunity to install solar or wind power to generate energy that is stored and distributed via the battery storage area. Further development may include the opportunity to install a small PSH facility. The development of these facilities at the site provides on-site, self-sustaining power. Build-up of the energy generation and storage facilities at the site would necessitate installation of maintenance facilities and additional access roads, and the presence of the solar, wind, and PSH facilities at the site would provide the opportunity for associated research. In turn, the hands-on research opportunities would spawn installation of research buildings and infrastructure. Eventually, the presence of the energy generation and storage technology, and the associated research facilities would provide educational opportunities, and perhaps eventually recreational opportunities.

The Energy Park concept distinguishes itself from traditional research facilities via:

1. The Energy Park concept represents a facility that highlights energy research and development while allowing for the opportunity to become a resource for middle and high school students in Southwest Virginia to be engaged via STEM-related energy projects.
2. The Energy Park concept serves as a testing ground and demonstration facility for large research projects, including offering private companies and researchers the opportunity to conduct field testing as opposed to simply bench scale testing.

3. The Energy Park concept provides an opportunity to develop a community education program to demonstrate to the public how new technologies work and what energy innovation research and development activities are underway.
4. The Energy Park concept intends that the products and successes from the research and development conducted at the Energy Park would contribute to development of technology to take advantage of the potential for Smart Energy generation and the associated economic benefits in Southwestern Virginia.
5. The Energy Park concept has the potential to eventually become a facility for bringing together local social engagement, which is rooted in the region's heritage, with cutting-edge technology to be developed at the facility in Southwest Virginia.

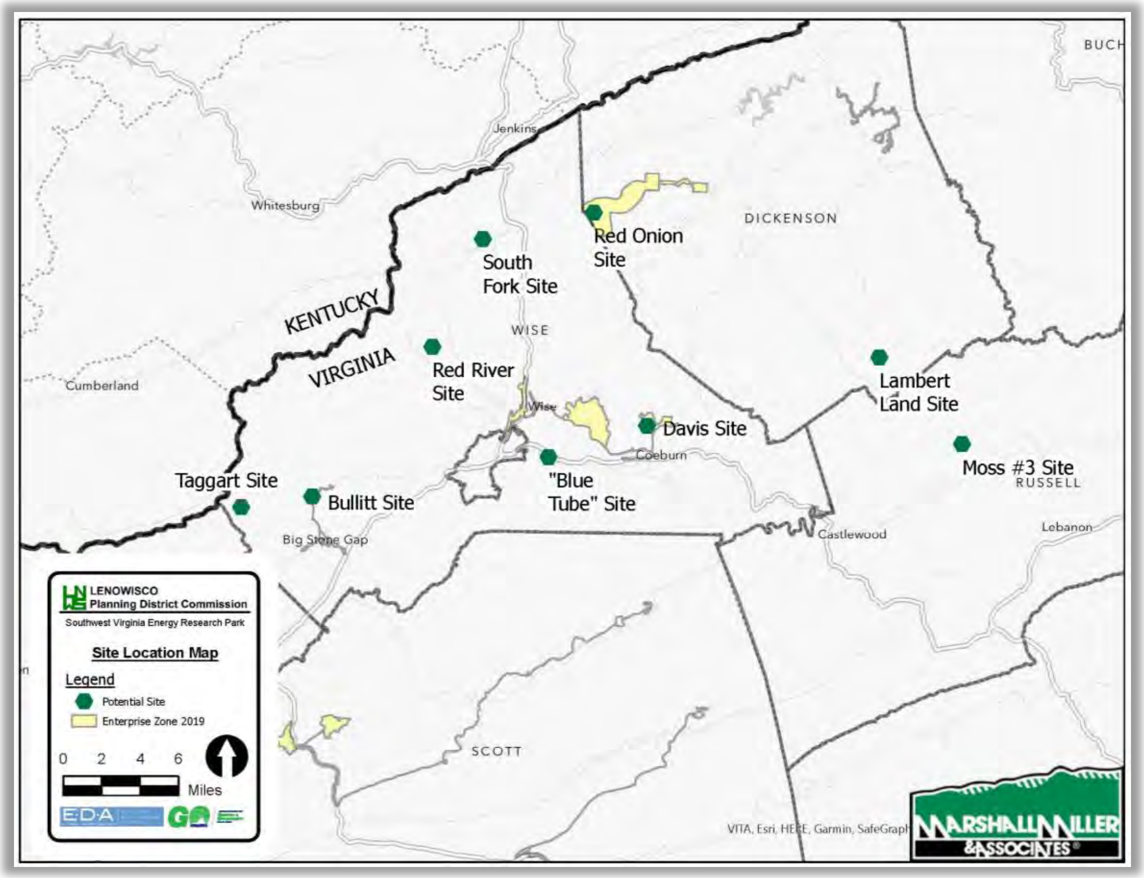
To accomplish the goals of locating a potential site for the Energy Park and further developing the vision of the Energy Park concept, the project team included **Marshall Miller & Associates, Inc. (*MM&A*)**, **HDR, Inc. (*HDR*)**, and **Thompson & Litton (*T&L*)**. The mix of project team members provided a combination of local Southwest Virginia experience with expert-level knowledge of related technical aspects. In general, MM&A provided a knowledge of local mining practices and the development of a database used for site vetting; HDR provided expert level knowledge specific to the potential development of PSH facilities in the Southwest Virginia area; and T&L provided an initial conceptual layout of the proposed Energy Park to facilitate further development and visualization of the park.

2 Site Location Vetting

Southwest Virginia presents unique challenges, as well as unique opportunities, when selecting a prime location for industrial development. Geology, topography, infrastructure, land and mineral ownership, existing civil-based infrastructure, and past and future mining and mineral development all necessitate careful consideration and evaluation. The site location vetting process followed by the project team is summarized below.

<u>Project Kick-off Meeting</u> – On Thursday, October 1, 2020, the MM&A project team (including MM&A, HDR, and T&L) met with personnel from the **Virginia Department of Mines, Minerals, and Energy (*DMME*)**, **Coalfield Strategies, LLC**, **GO Virginia**, and LENOWISCO to discuss project goals and to review general characteristics of an initial list of potential candidate sites to be considered for the Energy Park location. Major factors to be part of the location vetting process were also identified and discussed. *Figure 2-1* is a map indicating the general locations and names for sites considered during the vetting process. For reference, the figure also includes delineation of Enterprise Zones in the Southwest Virginia area, areas in which commercial and industrial businesses can receive incentives to set up or expand. As is evident from the figure, two of the potential Energy Park sites (Red Onion Site and Davis Site) are within or very near an Enterprise Zone.

Figure 2-1: Potential Energy Park Site Location Map (with 2019 Enterprise Zone)



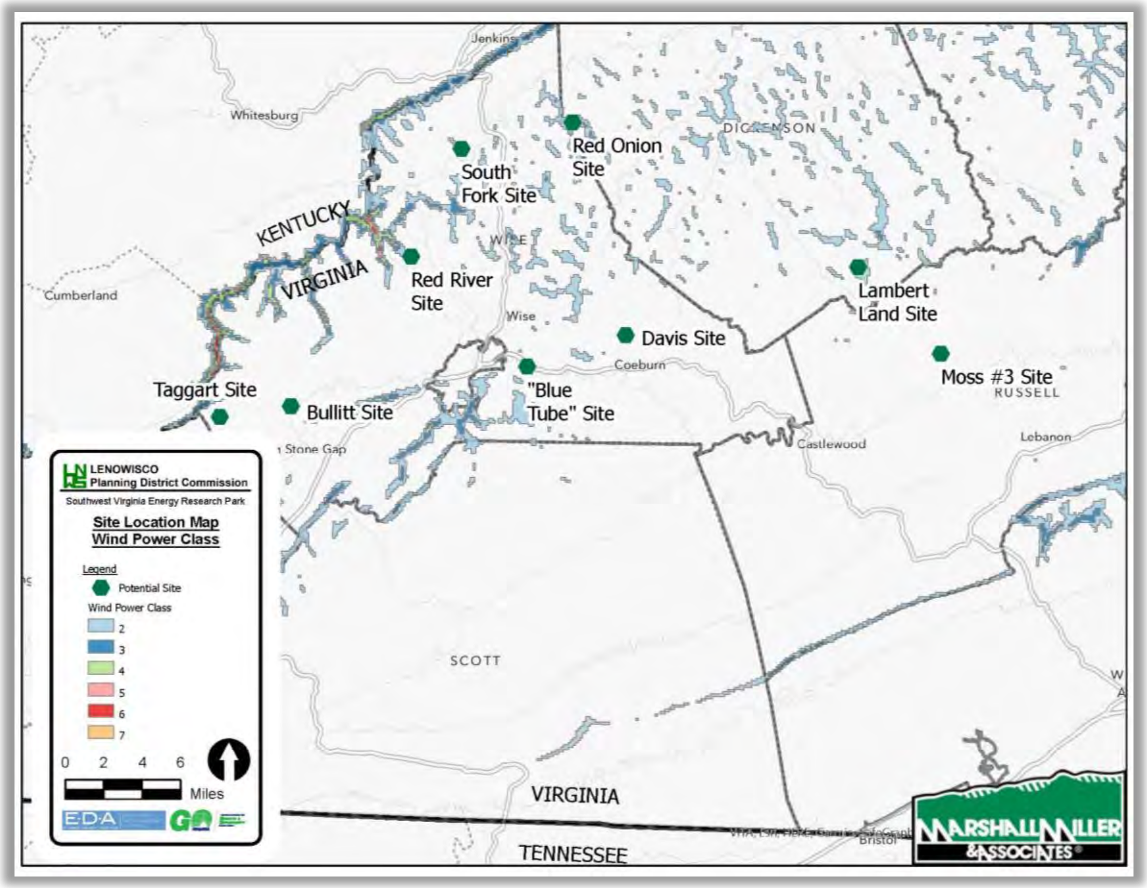
Data Compilation and Mapping – The project team collected relevant data from numerous sources including, but not limited to online sources, government agencies, in-house project files, and personal communication. The main mapping features compiled for the site vetting and selection process are briefly described below and *Table 2-1* summarizes the main sources of data.

Table 2-1: Summary of Main Map Features and Source Information

Map Features	Source
Administrative Boundaries	Virginia Administrative Boundaries dataset – Virginia Geographic Network (*VGIN*)
AML Features, Deep Mines, Surface Mines, and Gas Wells	Virginia Department of Mines, Minerals, and Energy (*DMME*)
Electric Transmission Lines and Substations	Homeland Infrastructure Foundation-Level Data (*HIFLD*)
Virginia Enterprise Zones	Virginia Department of Economic Development (*VDEP*)
Virginia Parcel Boundaries	Clearinghouse VGIN Base Map Data – Virginia Geographic Information Network (VGIN)
Wind Power Class 3 Areas	The National Renewable Energy Laboratory (*NREL*) – US Department of Energy
Digital Terrain Model (*DTM* Contour Data)	Virginia Base Mapping Program (VBMP) – Virginia Geographic Network (VGIN)
World Terrain Base Mapping	ARCGIS Online Base Map

- **Topographic Contour Data –** elevation contour lines representing features of the land surface, such as mountains, hills, and valleys. Topographic contour data was utilized to assess the maximum topographic relief in the vicinity of the potential Energy Park sites. The maximum topographic relief is a major design factor for determining the potential for installation of a PSH facility at any given location. See *Section 5* of this report for more detailed discussion.
- **Administrative Boundaries** - state, county, city, and town boundaries.
- **Roads and Existing Infrastructure –** mapping and classification of roadways and mapping of existing surface structures. The size and condition of access roads to a potential Energy Park site is a factor that has the potential to affect ease of access for both regular access by researchers and the general public.
- **Virginia Enterprise Zones** - geographic areas that have been granted special tax breaks, regulatory exemptions, or other public assistance to encourage private economic development and job creation. The Virginia Enterprise Zone (*VEZ*) program can provide two grant-based incentives, the Job Creation Grant (*JCG*) and the Real Property Investment Grant (*RPIG*), to qualified investors and job creators within those zones.
- **Virginia Parcel Boundaries** - legal representations of property ownership in the area.
- **Wind Power Class Areas** – Mapping of wind power classes within the Southwestern Virginia area was used to identify the best locations for wind turbine installation. Class 3 areas are considered suitable for most utility-scale wind turbine applications. *Figure 2-2* summarizes the wind power classes across the subject region. The figure indicates that Class 2 is most prevalent with only a few areas of greater than Class 2. As is evident from the figure, four of the sites considered are located within close proximity to at least Class 2 wind power. These sites include Lambert Land Site, Red Onion Site, South Fork Site, and Red River Site.

Figure 2-2: Wind Power Class Summary Map

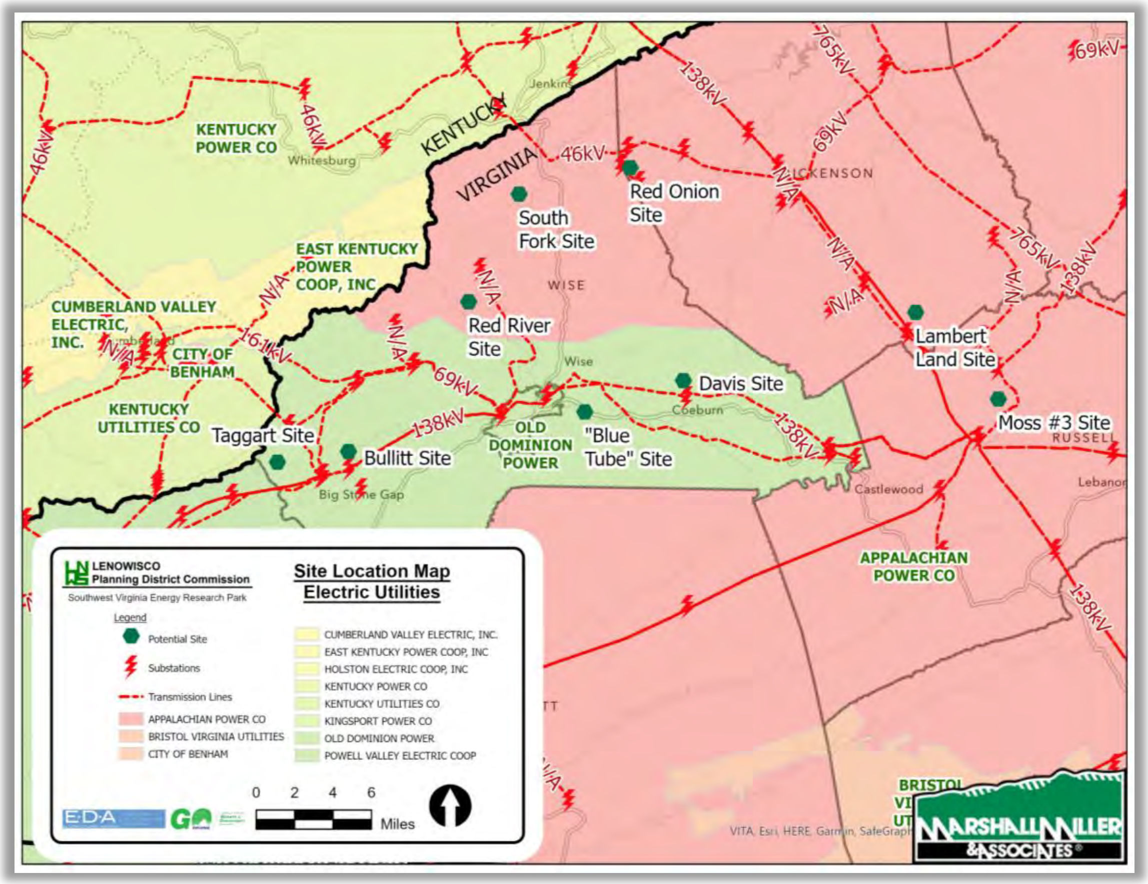


> **Solar Power Areas** – representation of areas suitable for solar field development. In general, the available information suggests that suitability for installation of solar power facilities in the subject areas is somewhat similar, with an emphasis put on the details of the site topography. Therefore, all of the sites have zones within them that would likely be suitable for solar power installation.

> **Electric Transmission Lines and Substations -** overhead power lines or underground power cables; necessary to carry high-voltage electricity over long distances and connect electricity generators with electricity consumers. Substations are facilities and equipment that switch, transform, and regulate electric power from transmission lines. Development of the Energy Park in close proximity to existing electrical infrastructure is a very significant consideration, as the energy generation and storage installations would have access to the area power grid. The electric utility provider for a particular site is also important, as cooperation between the Energy Park and the provider would be necessary. The need for installation of new electric transmission infrastructure would be expected to increase the cost, and therefore difficulty, of developing the Energy Park in some areas. *Figure 2-3* is a map indicating the locations of the potential sites considered for the Energy Park in relation to the location of transmission lines and substations. The map also provides a reference for electric utility providers associated with each potential

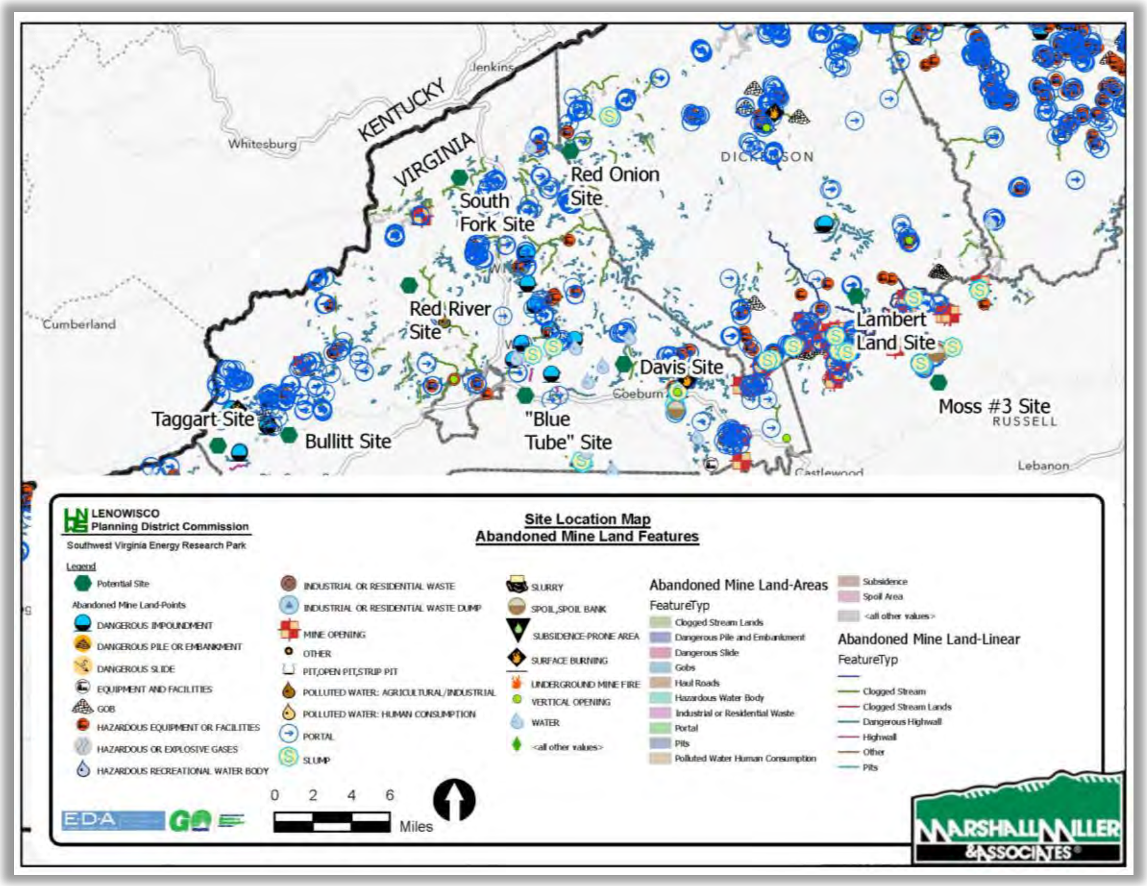
park site. As is evident from the map, most of the sites are located relatively close to a transmission line of some size.

Figure 2-3: Electric Utilities Summary Map (Transmission Lines and Substations)



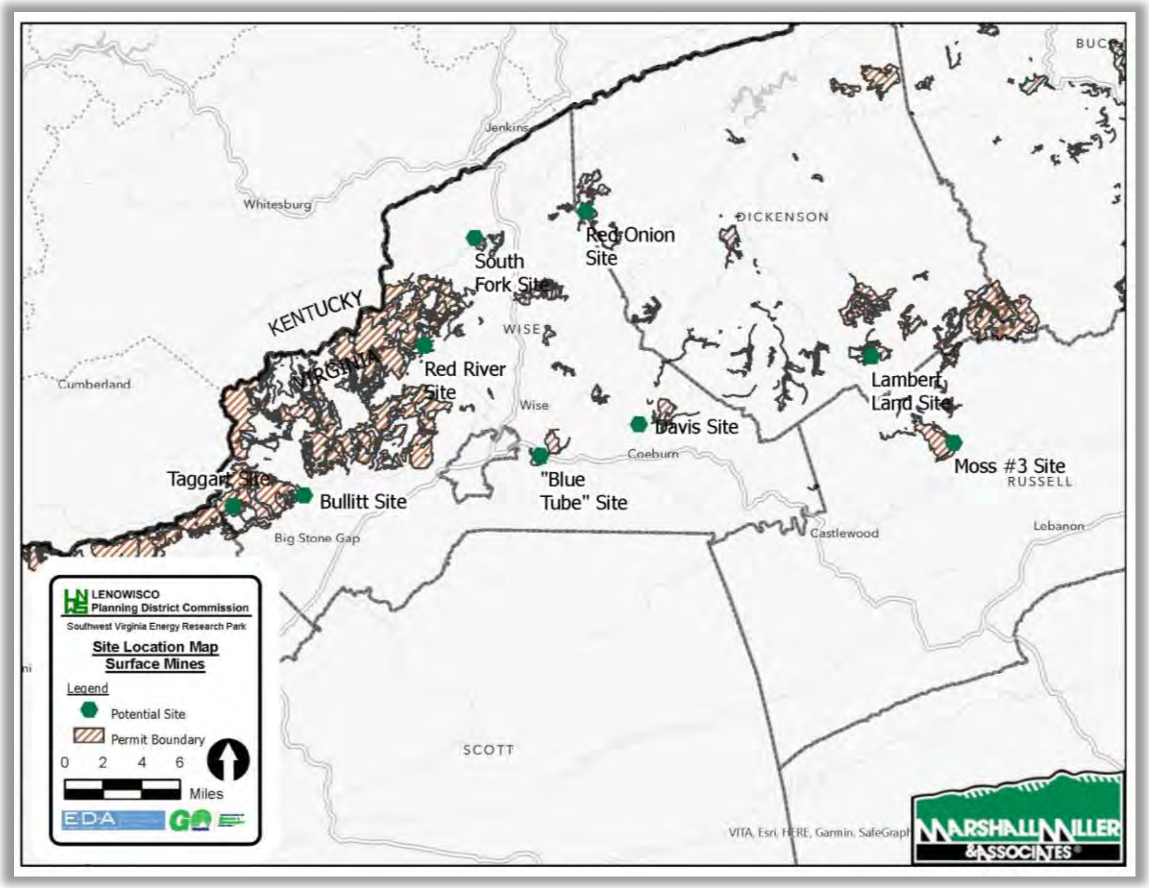
> **Abandoned Mine Land (*AML*) Features -** including landslides, stream sedimentation, hazardous structures, dangerous highwalls, subsidence, loss of water, acid mine drainage, and open-mine portals. *Figure 2-4* illustrates the position of the potential Energy Park sites relative to an array of different AML features. It is not unexpected that many, if not all, of the potential sites are located in close proximity to AML features. In general, proximity of a potential site to AML features is considered a positive attribute, as it presents opportunities for reclamation, funding, and research. Some of the AML features, such as refuse disposal areas, may actually provide unique opportunities for GeoEnergy research.

Figure 2-4: Abandoned Mine Lands (AML) Features Summary Map



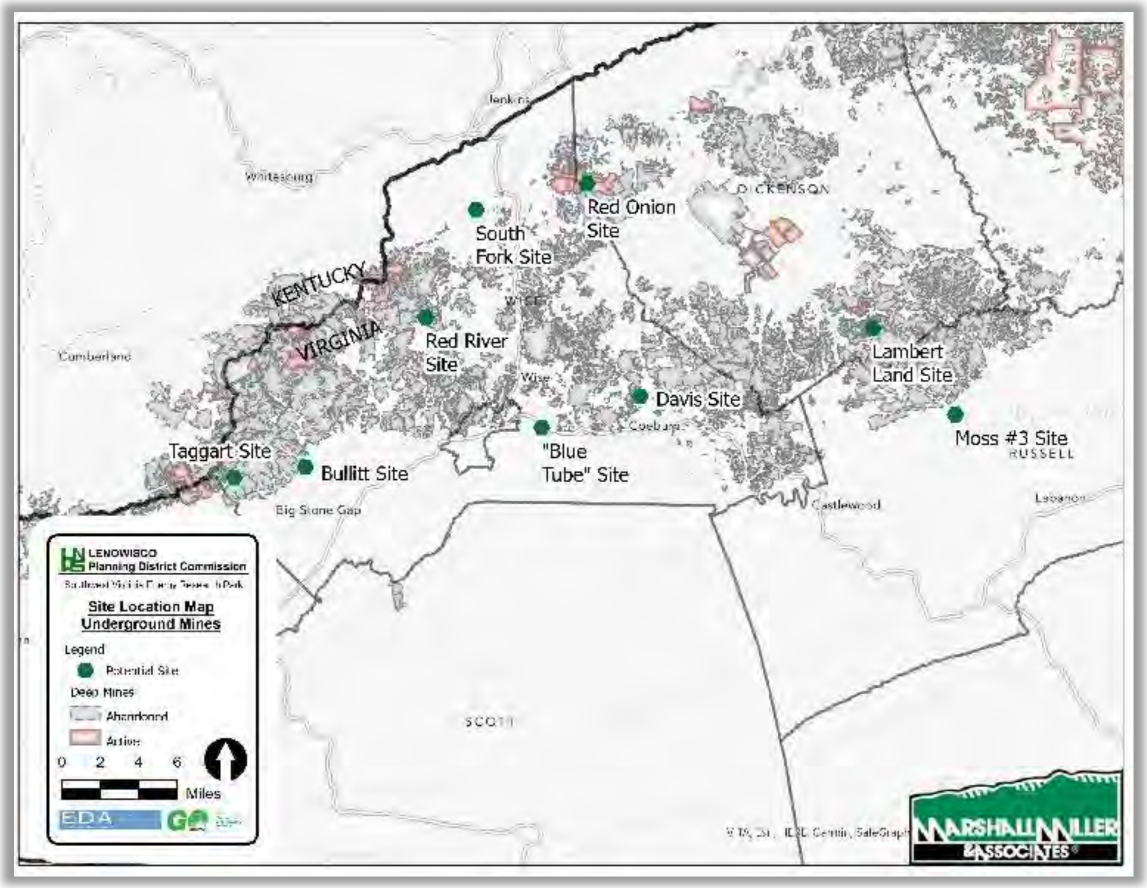
- **Surface Coal Mines** - permitted, active, and abandoned sites; previously surface mined areas present relatively flat terrain for surface development. Surface coal mines in Southwestern Virginia and other coalfield areas provide some of the best, and sometimes only, flat area for development of larger site infrastructure. Flat, previously surfaced mined areas provide development space for both buildings and installations of solar and wind energy generation systems. While abandoned and/or reclaimed sites provide flat ground and potential AML features, active surface mining can provide opportunity for planning of Energy Park-specific reclamation activities. *Figure 2-5* indicates that all of the potential sites either consist of previously surface mined areas or are in close proximity to previously surface mined areas.

Figure 2-5: Surface Mines Summary Map



- **Underground Coal Mines** - active and abandoned sites; inundated deep mines provide a water source and potential geothermal cooling area for renewable energy activities. The proximity of a potential Energy Park site to underground mining is considered a significant positive attribute. Abandoned underground mines have the potential to provide water for PSH or other facilities and inundated underground mines have the potential to function as geothermal reservoirs for alternative cooling of computer data storage centers. *Figure 2-6* indicates that six of the potential sites are located very near, or directly overlying underground mining. In particular, the Red Onion site is located close to both abandoned and active permit underground mines.

Figure 2-6: Underground Mines Summary Map

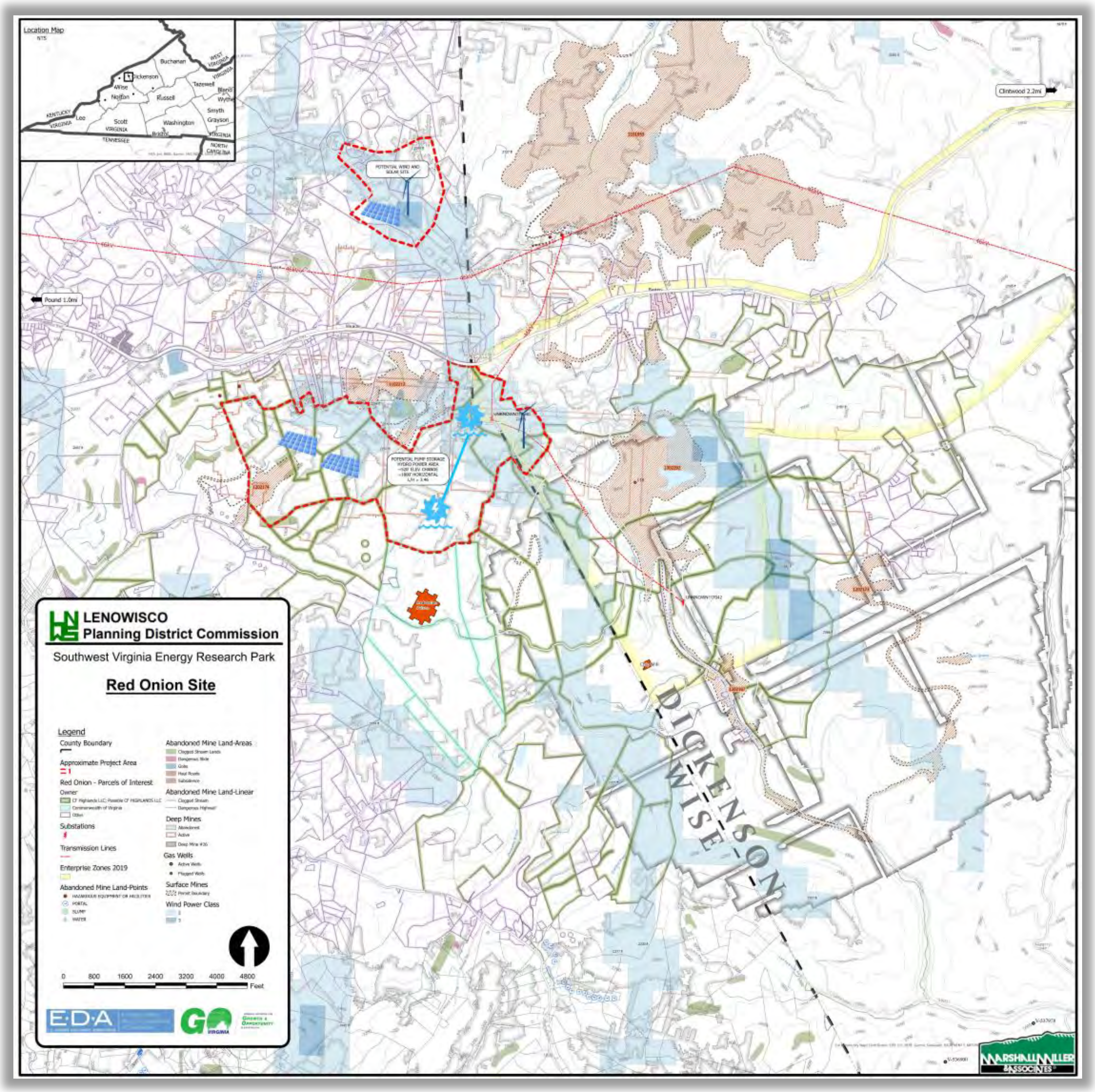


> **Gas Wells** - active and plugged/abandoned wellbores; gas wells present the potential for subsurface testing and monitoring.

> **Other Factors – Site availability and landowner relations** – During the course of the current assessment, the project team interacted with local agency representatives to understand the relative availability of land within each of the potential Energy Park site areas. While discussions are currently ongoing, the greatest progress with regard to land availability and opportunity for collaboration appears to be associated with the Red Onion site. While all factors associated with the development of the Energy Park are important, the availability and ease of access to a particular site is considered one of the most influential determining factors for selection.

Data for the factors described above was combined to create factor compilation maps for each of the potential candidate sites. The factor compilation maps were used to evaluate and compare the relative advantages and disadvantages amongst the potential sites. *Figure 2-7* is the Factor Compilation Map for the Red Onion Site. A large version of this map is included as *Attachment 1*.

Figure 2-7: Factor Compilation Map for Red Onion Site



3 Selection of Most Favorable Energy Park Site

The potential Energy Park sites were compared using the information discussed in the previous section. The current assessment suggests that the **Red Onion Site** currently presents the most favorable conditions. Major factors contributing to the selection of the Red Onion site include:

> Landowner relations and ongoing renewable energy development opportunities (solar)

> Partially within, or within close proximity to, Enterprise Zone

> Close proximity to underground and surface mines

> Existing previously mined flat areas and existing roads to site

> Includes AML features
> Includes areas of Class 2 and Class 3 Wind Power
> Relatively easy access and proximity to larger roadway
> Adequate topographic relief for potential PSH development
> Within relatively close proximity to electric transmission lines and substation

See *Attachment 1* for details of all factors associated with the Red Onion Site.

4 Conceptual Layout of Energy Park

To facilitate visualization of the Energy Park concept, T&L created three-dimensional renditions of a conceptual Energy Park layout. The conceptual layout includes wind turbines, solar field areas, upper and lower ponds (reservoirs) for a potential PSH facility, smaller buildings for battery storage and maintenance, a larger administration building, and roads and parking areas.

Figures 4-1 through *4-9* illustrate various views of the conceptual Energy Park layout. The three-dimensional topography used for the conceptual layout of the park is generated from one area within the Red Onion Site.

Figure 4-1: Conceptual Energy Park View 1 – Plan View

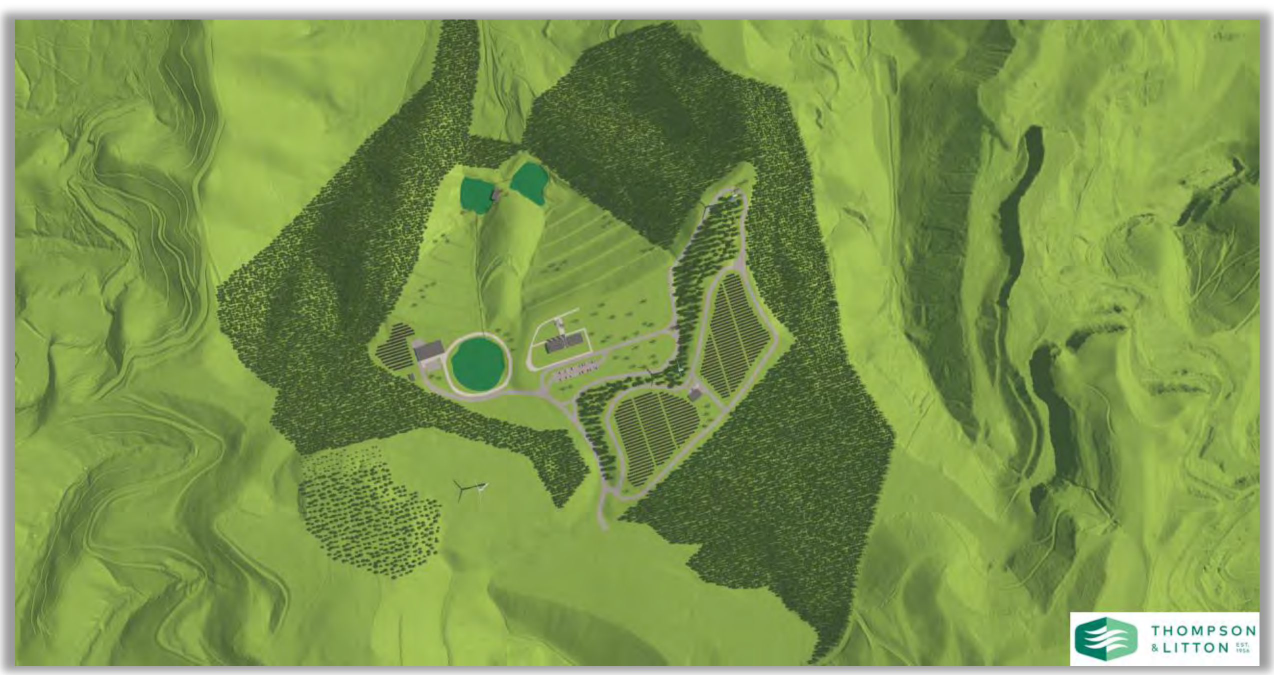


Figure 4-2: Conceptual Energy Park View 2 – Ponds for PSH, Solar Field, Wind Turbines, and Battery Storage

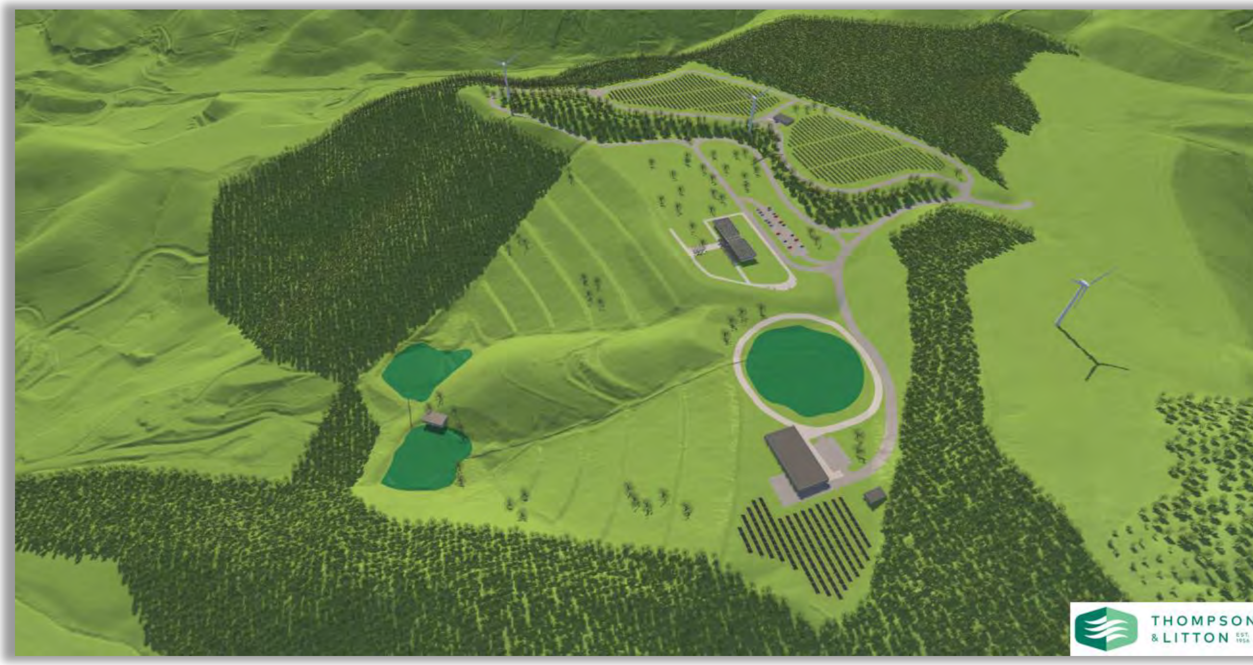


Figure 4-3: Conceptual Energy Park View 3 – Solar Field

Figure 4-4: Conceptual Energy Park View 4 – Solar Field with Wind Turbine

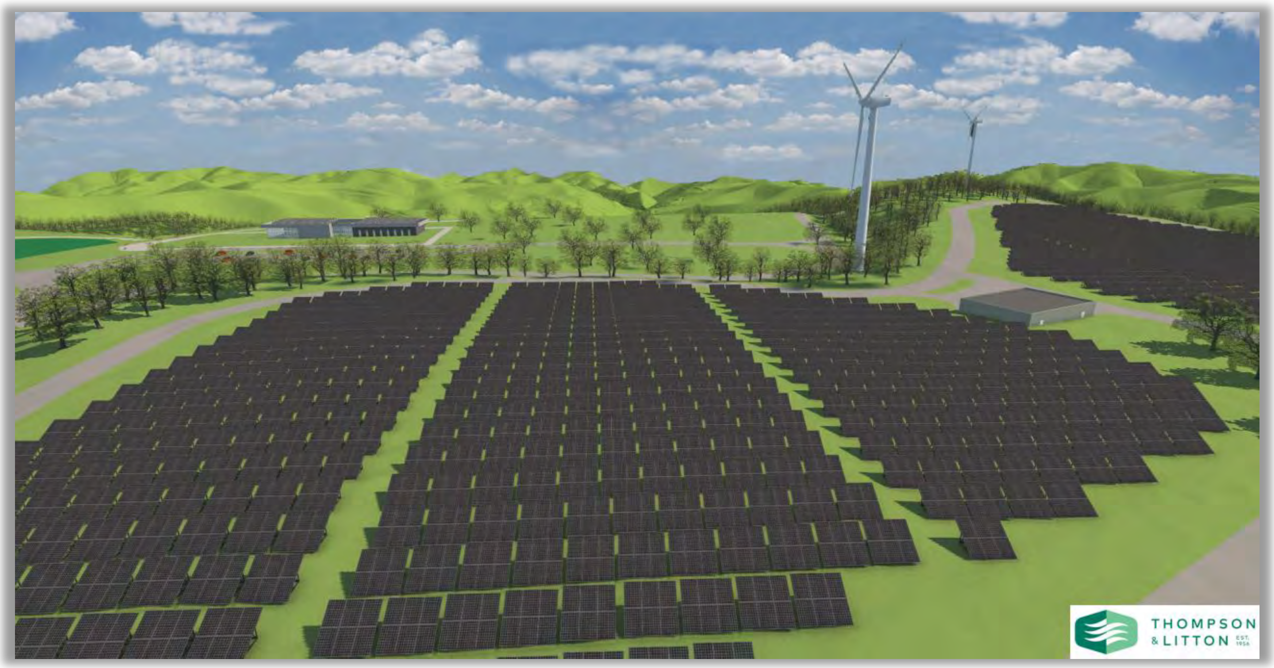


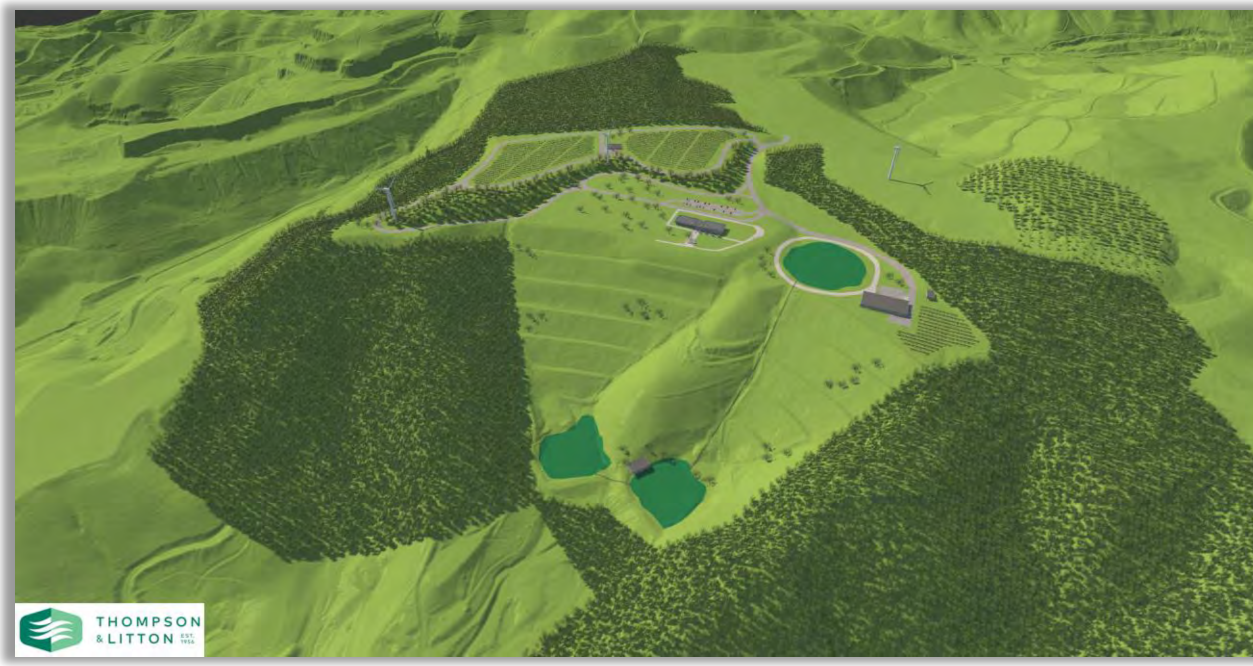
Figure 4-5: Conceptual Energy Park View 5 – Administration Building

Figure 4-6: Conceptual Energy Park View 6 – Administration Building and Parking

Figure 4-7: Conceptual Energy Park View 7 – Administration Building with Wind Turbines

Figure 4-8: Conceptual Energy Park View 8 – Solar Fields and Wind Turbines

Figure 4-9: Conceptual Energy Park View 9 – Existing Valley Fill with Ponds for Potential PSH



5 Pumped Storage Hydropower (*PSH*) Considerations

To aid with future consideration of pumped storage hydropower (*PSH*) installation as part of the Energy Park concept, HDR compiled a reference paper describing the main factors associated PSH facilities. The reference paper completed by HDR is included as *Attachment 2*. The PSH reference paper addresses the following objectives:

- Provide a general approach for performing a pumped storage screening and evaluation
- Perform a high-level conceptual evaluation for hypothetical installations having the following general attributes:
  - Install capacities of 1 megawatt (MW), 10 MW and 100 MW
  - Assumed static heads of 300 feet (ft), 600 ft, and 900 ft
  - Assumed continuous run times (generation mode) of 4 hours and 8 hours
- For the above scenarios, HDR will develop estimated active storage (acre-ft), generating discharge (cubic ft per second [*cfs*]), and water conveyance diameters (ft) assuming a single penstock.
- Provide an opinion-based range of installed costs ($/MW) for hypothetical 1 MW, 10 MW and 100 MW pumped storage projects using pertinent available public information and select HDR internal data.

6 Summary

This report outlines the basis of the Energy Park concept and presents the process and results of selecting a potential Energy Park location in Southwestern Virginia. Considering all of the factors, the most favorable site location is the Red Onion Site on the border of Wise and Dickenson Counties. The Red Onion Site ranks favorably in nearly all of the factors considered for the assessment, including landowner relations and potential ongoing site development. Factors may change with time and other potential sites may become available. Future development of the Energy Park concept may involve facilities in numerous locations.

The development of the Energy Park concept and of facilities at a chosen site is expected to occur incrementally as opportunities and funding arise. The overall design of the Energy Park should be completed in incremental, short-term steps, but with consideration and planning for overall long-term ideas. The development of the Energy Park must be flexible in order to take advantage of both anticipated and unexpected opportunities. Further efforts to progress the Energy Park concept must include continued landowner and potential investor relationship development. Partners may include electric utility companies, alternative energy companies, land management companies, mining companies, government agencies (federal, state, and local), universities, and private landowners.

Ultimately, the goal of the Energy Park concept is to provide a research and education facility in Southwestern Virginia that combines development of cutting-edge energy technology with local infrastructure and features, and positively contributes to economic growth and community well-being in the region.

ATTACHMENT

1

LARGE VERSION OF FACTOR COMPILATION MAP FOR RED ONION SITE

See separate file: Attachment 1 RedOnionLayout_Final.pdf

ATTACHMENT

2

PSH REFERENCE PAPER (HDR)

June 16, 2021

Mr. Steve Keim
Senior Vice President
Marshall Miller & Associates, Inc.

Via Email: steve.keim@mma1.com

Subject: Southwest Virginia Energy Research Park
Pumped Storage Project General Evaluation
Subconsultant Agreement September 22, 2020

Dear Mr. Keim:

As documented in your email dated 5/26/21 and in accordance with our Subconsultant Agreement, HDR is pleased to provide for your review and comment this DRAFT report containing general information, processes, and assumptions in support of Marshall Miller & Associates, Inc. (MMA) greater efforts to provide LENOWISCO Planning District Commission with location vetting support for a planned energy park in Southwest Virginia.

1 Project Understanding

HDR understands that a specific location (or potential locations) for the planned energy park has yet to be determined and hydroelectric pumped storage screening studies for specific sites have not been performed. With that said, HDR understands that MMA has requested HDR to provide information, criteria, and descriptions of processes commonly used for initial pumped storage site screening and evaluation. In support of this request, HDR will carry out the following tasks:

- Provide a general approach for performing a pumped storage screening and evaluation
- Perform a high-level conceptual evaluation for hypothetical installations having the following general attributes:
  - Install capacities of 1 megawatt (MW), 10 MW and 100 MW
  - Assumed static heads of 300 feet (ft), 600 ft, and 900 ft
  - Assumed continuous run times (generation mode) of 4 hours and 8 hours
- For the above scenarios, HDR will develop estimated active storage (acre-ft), generating discharge (cubic ft per second [cfs]), and water conveyance diameters (ft) assuming a single penstock.
- Provide an opinion-based range of installed costs ($/MW) for hypothetical 1 MW, 10 MW and 100 MW pumped storage projects using pertinent available public information and select HDR internal data.

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2 General Approach – Pumped Storage Site Screening and Attribute Evaluation

The scope of work outlined below follows a methodical and systematic approach for performing a hydroelectric pumped storage site screening and evaluation study:

2.1 Task 1: Project Kick-off Meeting

Participate in a project kick-off meeting to confirm all project objectives, available information, boundary conditions, operating assumptions and goals, study scope tasks, schedules, budgets, and deliverables.

2.2 Task 2: Data Collection and Review

Collect and review readily available geographic information system (GIS) data and relevant information available via public domain and/or otherwise made available by the client.

2.3 Task 3: Topographic and GIS Studies

Perform a high-level review of available topographic mapping and GIS data to form the basis for locating and sizing project features.

2.4 Task 4: Initial Site Screening Studies

Perform a GIS-based (with field reconnaissance where appropriate) site screening evaluation to identify potential pumped storage sites that generally adhere to the following criteria:

2.4.1 Criteria 1 – Avoid Where Possible Legal and Environmentally Sensitive Areas Excluded by Law

Potential sites must not intrude into areas for which federal, state, and local laws prohibit development for other purposes, such as:

- National parks/monuments/cemeteries
- Wild, scenic, and recreational rivers (or segments)
- Wilderness areas
- Critical habitat for threatened / endangered wildlife and aquatic species
- State, county, and city parks
- State protected rivers

2.4.2 Criteria 2 – Avoid Where Possible Areas Due to Incompatibility

Potential sites must not be located in areas that are incompatible for development, such as:

- Areas of national forests having protective management plans
- Rivers and streams managed for legislative-based fisheries
- Watersheds with restricted water rights
- Sites involving significant wetlands

- Urban areas
- Native American burial grounds
- Whitewater recreational areas
- Federal / state highways
- Active mines

2.4.3 Criteria 3 – Focus on Areas Where Possible with Accommodating Topographic Characteristics

Potential sites should meet the following approximate operating head (H) and water conductor length (L) relationship (EPRI 1990):

Operating Head (ft)	Maximum L/H Ratio
200 – 300	< 5
300 – 500	< 7
500 – 750	< 10
Greater than 750	< 12

2.4.4 Criteria 4 – Focus on Areas Where Possible with the Favorable Characteristics

Potential sites should feature the following favorable characteristics:

- Transmission access within a reasonable distance from site
- Access (roads, rail, etc.) within a reasonable distance from site
- Adequate available water source for initial fill and periodic make-up
- Topographic features accommodating for reservoir(s) construction
- Unit operating range - 70% to 100% of maximum head
- Maximum head
- Minimum water conductor length
- Adequate overburden above tunnels (for underground water conveyance feathers)
- Minimal reservoir operating constraints
- Minimal land inundation and ground disturbing activities
- Supporting infrastructure

2.4.5 Criteria 5 - Avoid Areas Where Possible with Unfavorable Geologic Characteristics (particularly for underground project features such as tunnels and caverns)

- High seismic risk/active faulting within project area
- Active volcanism
- Active landslides in Project Area
- Karst topography in Project Area
- Groundwater/subsurface conditions presenting leakage potential
- Deep chemical weathering profile
- Highly permeable rock/commercial aquifers/oil reservoir strata

- Soluble rock material
- Low strength, vibration sensitive, friable, highly abrasive, slaking of unlithified rock material
- Highly faulted, folded and fractured rock material
- Thinly laminated, structurally deformed fine-grained rock masses
- Stress relieved reservoir rims
- Soils conducive to liquefaction

2.4.6 Criteria 6 - Focus on Areas Where Possible Having Favorable Geologic Characteristics (particularly for underground project features such as tunnels and caverns)

- Strong, massive, durable, uniform homogeneous rock mass
- Crystalline, intrusive igneous, or metamorphic rock
- Massively bedded classic or non-solution carbonate rock
- High compressive strength, high cohesion, high modulus of deformation
- Resistant to cyclic hydrostatic loading
- Low permeability throughout project, without karst characteristics
- Adequate in-situ stress
- Little to moderate fracturing, jointing, faulting, and folding
- Low seismic risk
- Low volcanic risk
- Stable slopes and rims

2.4.7 Criteria 7 – For Abandoned Mine Sites Consider the Following

- Head and topographic relief
- Adequate and available source water
- Available infrastructure
- Mine stability
- Suitable flow rate (within underground mine)
- Recharge rate (within underground mine)
- Water quality
- Gases and methane
- Potential impact on future coal mining or gas production
- Proximity to other mines
- Available records

3 Preliminary Sizing for 1 MW, 10 MW and 100 MW Projects

HDR performed a high-level conceptual evaluation for hypothetical installations have the following general attributes:

- Install capacities of 1 MW, 10 MW and 100 MW
- Assumed static heads of 300 ft, 600 ft and 900 ft
- Assumed run times of 4 hours and 8 hours

3.1 Assumed Power Complex Configuration

Typical power complex configurations/profiles for large scale hydroelectric pumped storage are presented on Figure 1 (EPRI 1990). These projects generally include an upper and lower reservoir, water conveyance (above or below ground), and powerhouse (above or below ground) containing reversable pump-turbine units. Various factors such as topography, head, geology, and costs can influence what alternative is selected for a particular site. For this study, HDR assumed a general project configuration similar to Alternative F shown on Figure 1. For a small pumped storage project, the upper reservoir could either consist of a tank or impounded reservoir. The water conveyance is assumed to be an above ground steel penstock.

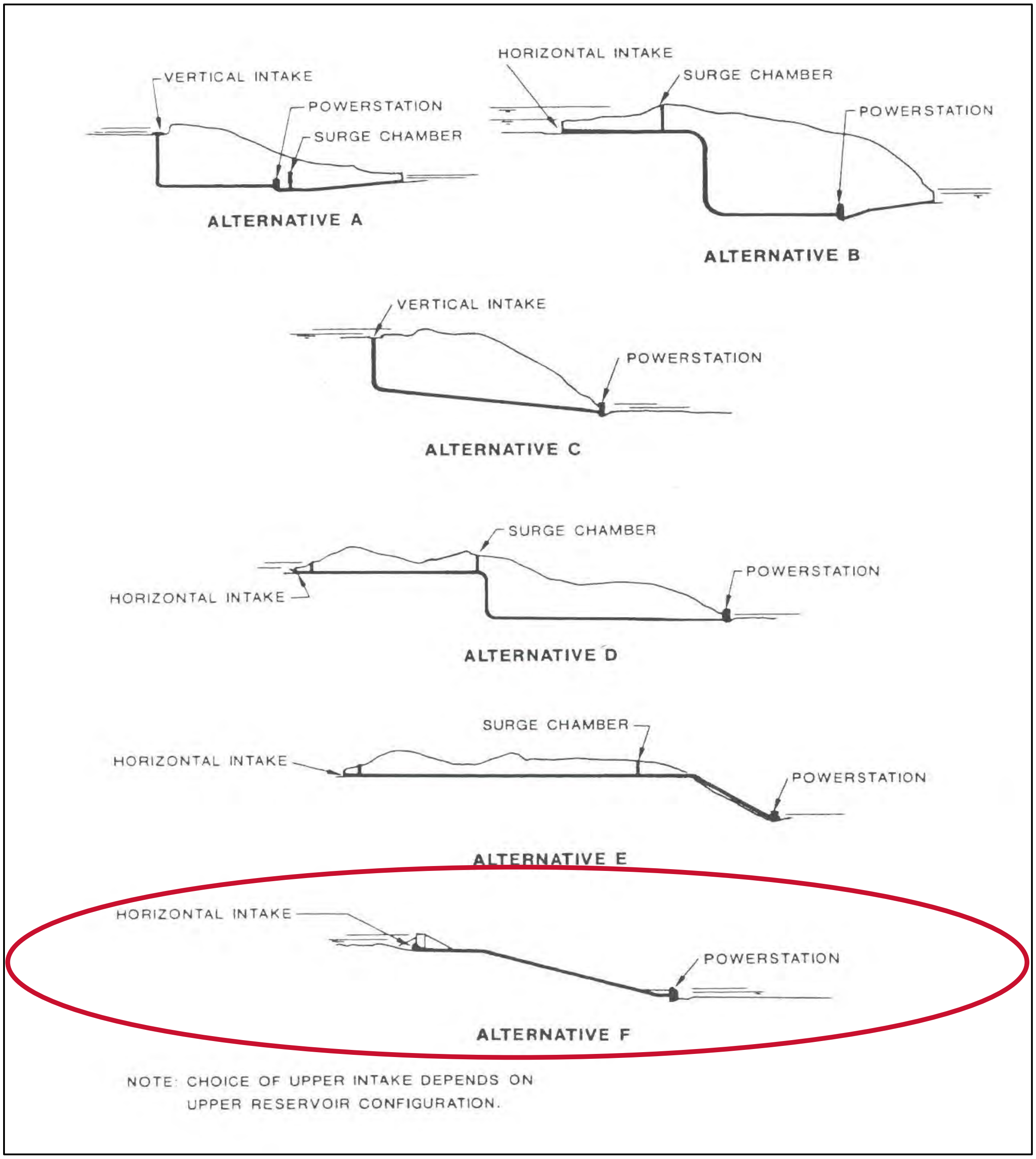

Figure 1. Alternative Pumped Storage Project Profiles

Source: EPRI (1990)

3.2 Estimated Energy Storage

The required energy storage can be estimated using the following relationship (EPRI 1990):

E = C x Hours of Storage

Where: E = Energy Storage (Megawatt hours [MWh])

C = Installed Capacity (1 MW, 10 MW and 100 MW)

Hours of Run Time (4 hours and 8 hours)

3.3 Estimated Upper and Lower Reservoir Active Storage

The active storage within the upper and lower reservoirs can be estimated using the following relationship (EPRI 1990):

$$E = 0.88\ HS \times 10^{-3}$$

Where: E = Energy Storage (MWh)

H = Average Gross Head (300 ft, 600 ft and 900 ft)

S = Required Active Storage (acre-ft)

3.4 Estimated Generating Discharge

The generating discharge can be estimated using the following relationship (EPRI 1990):

$$Q = 11{,}800\ C/He$$

Where: Q = Design Generating Discharge (cfs)

C = Rated Generating Capacity (MW)

H = Gross Head (ft)

e = Overall Generating Efficiency (assumed 0.86)

3.5 Preliminary Water Conductor Sizing

3.5.1 Generating Discharge

The number and size of water conductors can be estimated based on 1) an assumed maximum permissible flow velocity, which varies among the given features; 2) the assumed number of generating units; 3) an assumed maximum tunnel diameter; and 4) general constructability. Conductor sizes were estimated using the following relationship (EPRI 1990):

$$D > (1.273\ Q/V)^{0.5}$$

Where: D = Water Conductor Diameter (ft)

Q = Design Discharge (cfs)

V = Assumed Maximum Flow Velocity (ft/sec)

3.5.2 Flow Velocity

The maximum velocity with the penstock and draft tubes can estimated using the criteria (EPRI 1990) listed in Table 1.

Table 1. Flow Velocity Criteria

Maximum Head (ft)	Penstock Tunnel Velocity (fps)	Draft Tube Tunnel Velocity (fps)
200	17	6
300	18	8
500	20	10
1,000	25	13
1,500	28	15
2,200	32	17

3.6 Resulting Conceptual Pumped-Storage Attributes

Listed below are the estimate attributes for the following conceptual alternatives:

- Install capacities of 1 MW, 10 MW and 100 MW
- Assumed static heads of 300 feet, 600 feet and 900 feet
- Assumed continuous run times of 4 hours and 8 hours

Table 2. Conceptual Pumped Storage Attributes

Assumed Installed Capacity (MW)	1			10			100		
Assumed Static Head (ft)	300	600	900	300	600	900	300	600	900
Assumed Run Time (hours)	4	4	4	4	4	4	4	4	4
Energy Storage (MWh)	4	4	4	40	40	40	400	400	400
Required Active Storage (ac-ft)	15	8	5	152	76	51	1,515	758	505
Assumed Run Time (hours)	8	8	8	8	8	8	8	8	8
Energy Storage (MWh)	8	8	8	80	80	80	800	800	800
Required Active Storage (ac-ft)	30	15	10	303	152	101	3,030	1,515	1,010
Estimated Generating Discharge (cfs)	46	23	15	457	229	152	4,573	2,287	1,524
Preliminary Water Conveyance Diameter (ft)	2	1	1	5	4	3	17	12	10

4 Opinion-Based Range of Installed Construction Costs

Listed below are resources evaluated by HDR, including publicly available information and select HDR internal data materials, providing various opinions and ranges of installed costs ($/MW) for small, medium, and large scale hydroelectric pumped storage projects.

4.1 Resource Method No. 1 – HDR Internal Data Base of Screening Studies

Over the past 10 years HDR has performed various hydroelectric pumped storage screening studies for hundreds of U.S. sites ranging in size from 3 MW to over 2,000 MW, with most of the studies focused on larger scale - higher head projects. Many of these studies resulted in preliminary sizing of the various project elements (i.e. dams and reservoirs, water conveyance, size and number of units, tunnel lengths and diameters, powerhouse types, etc.) and AACE (Association for the Advancement of Cost Engineering) Class 5 Opinion of Probable Construction Cost (OPCC) (AACE 2020) development defined by the following:

- Level of Project Definition: Between 0 and 2 percent complete.
- End Usage: Concept Screening.
- Methodology: Capacity Factored, Parametric Models, Judgment, or Analogy.
- Expected Accuracy Range: Low = -20 to -50 percent; High = +30 to +100 percent.
- Definition of Estimate: Class 5 estimates are generally prepared based on limited information, and subsequently have wide accuracy ranges. As such, some companies and organizations have elected to determine that due to the inherent inaccuracies, such estimates cannot be classified in a conventional and systemic manner. Class 5 estimates, due to the requirements of end use, may be prepared within a very limited amount of time and with little effort expended. Often, little more than the proposed plant type, location, and capacity are known at the time of estimate preparation.
- Estimating Methods: Class 5 estimates virtually always use stochastic estimating methods such as cost/capacity curves and factors, scale of various factors, and other parametric and modeling techniques.

Figure 2 contains a select sample of OPCCs developed, escalated to 2021 dollars, using USACE (2021) escalations.

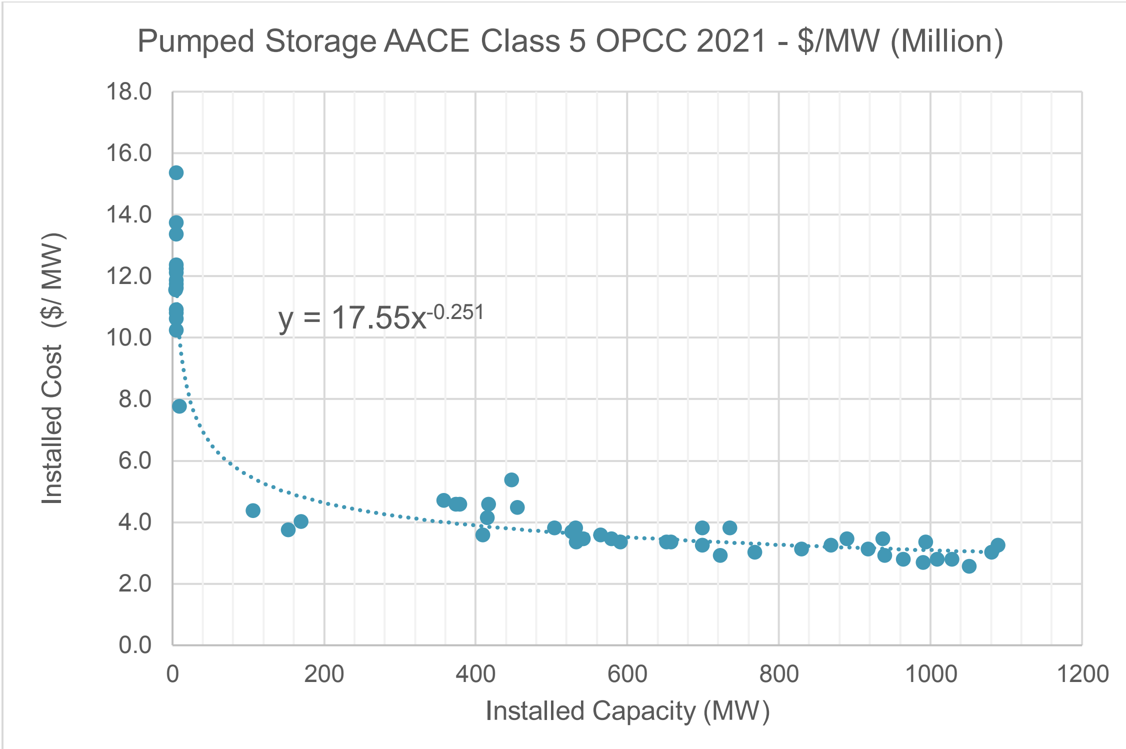

Figure 2. HDR Select Pump Storage Project Installed Cost 2021 (AACE Class 5)

These data suggest the following:

- Projects having an installed capacity of 1 MW could cost on the order of $8,000/kilowatt (kW) to $16,000/kW).
- Projects having an installed capacity of 10 MW could cost on the order of $6,000/kW to $12,000/kW.
- Projects having an installed capacity of 100 MW could cost on the order of $4,000/kW to $8,000/kW.
- Projects having an installed capacity of 1000 MW could cost on the order of $2,000/kW to $4,000/kW.

4.2 Resource Method No. 2 – International Renewable Energy Agency 2012 Study

In June 2012, the International Renewable Energy Agency (IRENA 2012) published “Renewable Energy Technologies: Cost Analysis Series, Volume 1: Power Sector, Issue 3/5”. Listed below in Table 3 are:

- Reported installed costs of large (100 MW +) and small (1 to 20 MW) conventional hydro projects in 2010 US Dollars.
- HDR applied escalation factors 2010 to 2021 U.S. dollars (USACE 2021)

- HDR assumed 1.3 cost adjustment factor to convert the conventional costs to pump storage costs, primarily due to increase storage reservoirs and reversible pump-turbine unit equipment costs.

Table 3. IRENA Escalated Installed Cost Data

Size*	Installed Capacity (MW)*	Installed Costs (2010 USD/kW)*	Escalation Factor (2010 to 2021)**	Cost Factor Conventional to PS	PS Installed Costs (2021 USD/kW)
Large	100 +	1050 - 7650	1.3	1.3	1,800 – 12,900
Small	1 to 20	1300 - 8000	1.3	1..3	2,200 – 13,500

*Source: IRENA 2012
**Source: USACE 2021
Note: USD= U.S. dollars

HDR Observations

Utilizing the assumptions noted above, the installed costs for small and large hydroelectric pumped storage projects generally fall in the range of the HDR data base (Resource Method No. 1).

For additional information, a copy of the IRENA Renewable Energy Technologies: Cost Analysis Series Hydropower is provided as Attachment 1.

4.3 Resource Method No. 3 – Oak Ridge National Laboratory, Hydropower Baseline Cost Modeling, January 2015

In January 2015, Oak Ridge National Laboratory (ORNL 2015) published “Hydropower Baseline Cost Modeling, January 2015”. This purpose of this document was to present the background, framework, methodology, and results of the collection of data and the development of the parametric models to predict the initial capital costs (ICC) of hydropower projects. The resulting cost models (in 2012$) for Pumped Storage Hydropower and New Stream Reach (NSR) Site Development Projects are provided below in Table 4. See Table 5 for the ORNL cost model for NSR projects.

Table 4. ORNL Cost Model Data

Resource Category	Cost Model Equation (ICC in 2012$, P in MW: H in ft)
New Stream Reach Site Development Projects	$ICC = 8{,}717{,}830\ P^{0.975}\ H^{-0.265}$
Pumped Storage Hydropower Projects (< 500 MW)	$ICC = 2{,}590{,}713\ P^{0.96}$

Clarifications:

1) The data set for pumped storage included 83 projects ranging in installed capacities between 85 MW and 2,000 MW, with the majority of projects in the capacity range of 200 MW to 2,000 MW; therefore these may not reflect the costs for small pumped storage projects.
2) The data set for the new stream reach development included 84 conventional projects with installed capacities between less than 1 MW to around 100 MW. HDR also assumes the new stream reach projects most likely do not include any notable storage in the upper reservoir, nor a lower reservoir. In an attempt to associate the new stream reach cost data to reflect pumped storage cost data, HDR assumed a 1.3 cost factor to escalate the new stream reach

project costs to reflect an opinion of pump storage cost, primarily to allocate additional costs for upper and lower reservoirs and more expensive reversible pump-turbine equipment.

Table 5. Pumped Storage ICC using ORNL NSR Cost Model

Installed Capacity (MW)	Head (ft)	ORNL ICC NSR (2012 $ Million)	Escalation Factor (2012 to 2021)	Conventional to Pumped Storage Escalation Factor	ORNL Pumped Storage ICC (2021 $/kW)
1	300	4.4	1.2	1.3	6,900
1	600	4.1	1.2	1.3	6,400
1	900	3.9	1.2	1.3	6,100
10	300	42	1.2	1.3	6,600
10	600	38	1.2	1.3	5,900
10	900	36	1.2	1.3	5,600
100	300	392	1.2	1.3	6,100
100	600	361	1.2	1.3	5,600
100	900	343	1.2	1.3	5,300

HDR Observations:

The ORNL average installed cost per MW for small stream reach projects was on the order of $5,500 /kW (2021) using the escalation factors noted above. Assume a 1.3 cost adjustment factor (conventional new stream reach to pump storage), this would yield approximately $6,500/kW (2021) falling in the range of both the HDR (Resource Method No. 1) and IRENA (Resource Method No. 2) data base.

For additional information, a copy of the ORNL Hydropower Baseline Cost Modeling 2-15 Report Cover and Executive Summary is provided as Attachment 2.

4.4 Resource Method No. 4 – Modular Pumped Storage Hydropower Feasibility and Economic Analysis, U.S. Department of Energy, February 13-17, 2017

The U.S. Department of Energy via the Energy Efficiency & Renewable Energy funded a project titled Modular Pumped Storage Hydropower Feasibility and Economic Analysis (USDOE 2017). The results of this study are outlined in a presentation by Boualem Hadjerioua with Oak Ridge National Laboratory dated February 2017. The stated objectives of this project were as follows:

- Assess the cost and design dynamics of small modular hydroelectric pumped storage development
- Explore whether the benefits of modularization are sufficient to outweigh the economies of scale inherent to utility scale development, and
- Measure the economic competitiveness of modular pumped storage against batteries.

Of particular interest to this white paper are the pumped storage case studies performed for 1) Coal Mine (5 MW) and ORNL Campus. Listed below is a high-level summary of the two selected case studies:

4.4.1 Coal Mine (5 MW)

This scenario uses water contained within an abandoned coal mine as the lower pool with an upper reservoir constructed above ground. The static head was approximately 500 ft. The plant uses a conventional generation unit and a separate pump, both connected to a single bifurcated water conveyance system. Listed below is a high-level summary of the study conclusions:

- Initial construction costs (2015 dollars): $1700/kW to $2400/kW (10 hours of storage)
- Closed loop
- Existing infrastructure
- Regulatory uncertainty and poor regional economic indicators
- Potential challenges associated with lower pool operations and water elevations

4.4.2 ORNL Campus (5 MW)

This scenario is believed to contain upper reservoir storage tanks, an existing lower reservoir and steel penstocks for water conveyance. The static head or equipment package was not provided. Listed below is a summary of the study conclusions:

- Initial construction costs (2015 dollars): $4100/kW to 4700 $/kW (10 hours of storage)
- Open loop
- No Existing infrastructure other than an existing lower reservoir
- High costs and lower market revenue

HDR Observations:

HDR conducted a similar screening study in 2011 that evaluated constructing 5 MW pumped storage projects in a similar setting as noted above. The results of HDR's study concluded an initial construction costs on the order of $10,000/kW to 12,000 $/kW (2011 dollars). Therefore, the 2015 cost analysis summarized above appears to be low based on HDR's similar study.

For additional information, a copy of the Modular Pumped Storage Hydropower Feasibility Study and Economic Analysis PowerPoint is provided as Attachment 3.

4.5 Resource Method No. 5 – Hybrid Renewable Modular Closed-Loop Scalable PSH System by Hector Medina and Thomas Eldredge, PhD, January 2021

Attachment 4 contains a Technology Briefing Paper (Medina and Eldredge 2021) provided to HDR by the authors/inventors describing their patent-pending concept described as a "hybrid, closed-loop, scalable pumped storage hydro (h-mcs-PSH) and renewable" system with an approximate power capacity range of 0.1 to 10 MW. The pumped storage concept as described includes polymeric tanks as upper and lower reservoirs, a powerhouse containing high efficiency vertical-shaft pump-turbine system, penstocks, solar panels (if desired) and transmission. Listed below in Table 6 are the author's stated installed costs (2019 $/kW) for various system capacities.

Table 6. Medina/Eldredge Installed Costs for Various Installed Capacity Projects

Installed Capacity (MW)	Approximate Installed Costs w/o Solar (2019$/kW)	Approximate Installed Costs w/Solar (2019$/kW)
.1	15,000	17,000
.5	10,000	12,000
1.0	7,000	9,000
3.0	4,000	6,000
5.0	3,000	5,000
10.0	2,000	4,000

For additional information, a copy of the Hybrid Renewable Modular Closed-Loop Scalable PSH System paper is provided as Attachment 4. The contact information for the authors is as follows:

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5 Conclusions

- Hydroelectric pumped storage project configurations are site specific.
- The technical/economic feasibility and associated construction costs/schedule for hydroelectric pumped storage projects are very sensitive to various factors, such as geology, topography, environment/regulatory setting, and available infrastructure (roads, transmission, source water, etc.) and resources.
- There is no known available as-built construction cost data for small pumped storage hydropower projects.
- For the purpose of this early development study, HDR recommends the following OPCC range for constructing a small hydroelectric pumped storage project:
    - Projects having an installed capacity of 1 MW or less could cost on the order of $6,000/kW to $16,000/kW.
    - Projects having an installed capacity of approximately 10 MW could cost on the order of $4,000/kW to $12,000/kW.
    - Projects having an installed capacity of 100 MW could cost on the order of $3,000/kW to $8,000$kW.
    - Projects having an installed capacity of 1000 MW could cost on the order of $2,000/kW to $4,000/kW.

- Once a site screening study has been performed and a project location identified, a site specific configuration study can be advance with greater accuracy and more accurate opinion of probable construction costs (OPCC) developed in accordance with the Association for the Advancement of Cost Engineering (AACE) guidelines.

If you have any questions, comments or recommendations regarding this draft submittal, please contact me at ron.grady@hdrinc.com or 704-502-6991.

Sincerely,
HDR Engineering, Inc.

Ron Grady, PE
Vice President

6 References

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Attachment 1

International Renewable Energy Agency (IRENA) Renewable Energy Technologies: Cost Analysis Series. Volume 1: Power Sector, Issue 3/5. June 2012.

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IRENA WORKING PAPER

International Renewable Energy Agency

RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES

Volume 1: Power Sector

Issue 3/5

Hydropower

June 2012

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation dedicated to renewable energy.
In accordance with its Statute, IRENA's objective is to "promote the widespread and increased adoption and the sustainable use of all forms of renewable energy". This concerns all forms of energy produced from renewable sources in a sustainable manner and includes bioenergy, geothermal energy, hydropower, ocean, solar and wind energy.
As of May 2012, the membership of IRENA comprised 158 States and the European Union (EU), out of which 94 States and the EU have ratified the Statute.

Acknowledgement

This paper was prepared by the IRENA Secretariat. The paper benefitted from an internal IRENA review, as well as valuable comments and guidance from Ken Adams (Hydro Manitoba), Emanuel Branche (EDF), Professor LIU Heng (International Center on Small Hydropower), Truls Holtedahl (Norconsult AS), Frederic Louis (World Bank), Margaret Mann (NREL), Judith Plummer (Cambridge University), Richard Taylor (IHA) and Manuel Welsch (KTH).

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This working paper is available for download from www.irena.org/Publications

Disclaimer

Preface

Renewable power generation can help countries meet their sustainable development goals through provision of access to clean, secure, reliable and affordable energy.

Renewable energy has gone mainstream, accounting for the majority of capacity additions in power generation today. Tens of gigawatts of wind, hydropower and solar photovoltaic capacity are installed worldwide every year in a renewable energy market that is worth more than a hundred billion USD annually. Other renewable power technology markets are also emerging. Recent years have seen dramatic reductions in renewable energy technologies' costs as a result of R&D and accelerated deployment. Yet policy-makers are often not aware of the latest cost data.

International Renewable Energy Agency (IRENA) Member Countries have asked for better, objective cost data for renewable energy technologies. This working paper aims to serve that need and is part of a set of five reports on hydropower, wind, biomass, concentrating solar power and solar pholtovoltaics that address the current costs of these key renewable power technology options. The reports provide valuable insights into the current state of deployment, types of technologies available and their costs and performance. The analysis is based on a range of data sources with the objective of developing a uniform dataset that supports comparison across technologies of different cost indicators - equipment, project and levelised cost of electricity – and allows for technology and cost trends, as well as their variability to be assessed.

The papers are not a detailed financial analysis of project economics. However, they do provide simple, clear metrics based on up-to-date and reliable information which can be used to evaluate the costs and performance of different renewable power generation technologies. These reports help to inform the current debate about renewable power generation and assist governments and key decision makers to make informed decisions on policy and investment.

The dataset used in these papers will be augmented over time with new project cost data collected from IRENA Member Countries. The combined data will be the basis for forthcoming IRENA publications and toolkits to assist countries with renewable energy policy development and planning. Therefore, we welcome your feedback on the data and analysis presented in these papers, and we hope that they help you in your policy, planning and investment decisions.

Dolf Gielen

Director, Innovation and Technology

Contents

Key findings

1. **Average investment costs** for large hydropower plants with storage typically range from as low as USD 1 050/kW to as high as USD 7 650/kW while the range for small hydropower projects is between USD 1 300/kW and USD 8 000/kW. Adding additional capacity at existing hydropower schemes or existing dams that don't have a hydropower plant can be significantly cheaper, and can cost as little as USD 500/kW.

TABLE 1: TYPICAL INSTALLED COSTS AND LCOE OF HYDROPOWER PROJECTS

	Installed costs (USD/kW)	Operations and maintenance costs (%/year of installed costs)	Capacity factor (%)	Levelised cost of electricity (2010 USD/kWh)
Large hydro	1 050 – 7 650	2 – 2.5	25 to 90	0.02 – 0.19
Small hydro	1 300 – 8 000	1 – 4	20 to 95	0.02 – 0.27
Refurbishment/upgrade	500 – 1 000	1 – 6		0.01 – 0.05

Note: The levelised cost of electricity calculations assume a 10 % cost of capital

2. **Annual operations and maintenance costs** (O&M) are often quoted as a percentage of the investment cost per kW. Typical values range from 1% to 4 %. Large hydropower projects will typically average around 2 % to 2.5 %. Small hydropower projects don't have the same economies of scale and can have O&M costs of between 1% and 6 %, or in some cases even higher.

3. **The cost of electricity generated** by hydropower is generally low although the costs are very site-specific. The levelised cost of electricity (LCOE) for hydropower refurbishments and upgrades ranges from as low as USD 0.01/kWh for additional capacity at an existing hydropower project to around USD 0.05/kWh for a more expensive upgrade project assuming a 10 % cost of capital. The LCOE for large hydropower projects typically ranges from USD 0.02 to USD 0.19/kWh assuming a 10 % cost of capital, making the best hydropower power projects the most cost competitive generating option available today. The LCOE range for small hydropower projects for a number of real world projects in developing countries evaluated by IRENA was between USD 0.02 and USD 0.10/kWh, making small hydro a very cost competitive option to supply electricity to the grid, or to supply off-grid rural electrification schemes. Very small hydropower projects can have higher costs than this and can have an LCOE of USD 0.27/kWh or more for pico-hydro systems.

4. **Significant hydropower** potential remains unexploited. The technical potential is some 4.8 times greater than today's electricity generation. The total worldwide technical potential for hydropower is estimated at 15 955 TWh/year.

5. **Hydropower, when associated with storage** in reservoirs, contributes to the stability of the electrical system by providing flexibility and grid services. Hydropower can help with grid stability, as spinning turbines can be ramped up more rapidly than any other generation source. Additionally, with large reservoirs, hydropower can store energy over weeks, months, seasons or even years. Hydropower can therefore provide the full range of ancillary services required for the high penetration of variable renewable energy sources, such as wind and solar.

List of tables

List of figures

1. Introduction

Renewable energy technologies can help countries meet their policy goals for secure, reliable and affordable energy to expand electricity access and promote development. This paper is part of a series on the cost and performance of renewable energy technologies produced by IRENA. The goal of these papers is to assist government decision-making and ensure that governments have access to up-to-date and reliable information on the costs and performance of renewable energy technologies.

Without access to reliable information on the relative costs and benefits of renewable energy technologies it is difficult, if not impossible, for governments to arrive at an accurate assessment of which renewable energy technologies are the most appropriate for their particular circumstances. These papers fill a significant gap in publically available information because there is a lack of accurate, comparable, reliable and up-to-date data on the costs and performance of renewable energy technologies. The rapid growth in installed capacity of renewable energy technologies and the associated cost reductions mean that even data one or two years old can significantly overestimate the cost of electricity from renewable energy technologies although this is not generally the case for hydropower, which is a mature technology. There is also a significant amount of perceived knowledge about the cost and performance of renewable power generation that is not accurate, or indeed even misleading. Conventions on how to calculate cost can influence the outcome significantly, and it is imperative that these are well-documented.

The absence of accurate and reliable data on the cost and performance of renewable power generation technologies is therefore a significant barrier to the uptake of these technologies. Providing this information will help governments, policy-makers, investors and utilities make informed decisions about the role renewables can play in their power generation mix. This paper examines the fixed and variable cost components of hydropower by country and region and provides the levelised cost of electricity from hydropower, given a number of key assumptions. This up-to-date analysis of the costs of generating electricity from hydropower will allow a fair comparison of hydropower with other generating technologies.[1]

1.1 DIFFERENT MEASURES OF COST

Cost can be measured in a number of different ways, and each way of accounting for the cost of power generation brings its own insights. The costs that can be examined include equipment costs (e.g. wind and hydropower turbines, PV modules, solar reflectors), replacement costs, financing costs, total installed cost, fixed and variable operating and maintenance costs (O&M), fuel costs and the levelised cost of energy (LCOE).

The analysis of costs can be very detailed, but for purposes of comparison and transparency, the approach used here is a simplified one. This allows greater scrutiny of the underlying data and assumptions, improved transparency and confidence in the analysis, as well as facilitating the *comparison* of costs by country or region for the same technologies in order to identify what are the key drivers in any differences.

The three indicators that have been selected are:

- Equipment cost (factory gate "free on board" and delivered at site "cost, insurance and freight");
- Total installed project cost, including fixed financing costs[2]; and
- The levelised cost of electricity LCOE.

1 IRENA, through its other work programmes, is also looking at the costs and benefits, as well as the macro-econimic impacts, of renewable power generation technologies. See WWW.IRENA.ORG for further details.

2 Banks or other financial institutions will often charge a fee, usually a percentage of the total funds sought, to arrange the debt financing of a project. These costs are often reported separately under project development costs.

The analysis in this paper focuses on estimating the cost of hydropower energy from the perspective of an individual investor, whether it is a state-owned electricity generation utility, an independent power producer, an individual or a community looking to invest in renewables (Figure 1.1). The analysis excludes the impact of government incentives or subsidies, system balancing costs associated with variable renewables and any system-wide cost-savings from the merit order effect[3]. Further, the analysis does not take into account any CO_2 pricing, nor the benefits of renewables in reducing other externalities (e.g. reduced local air pollution, contamination of natural environments). Similarly, the benefits of renewables being insulated from volatile fossil fuel prices have not been quantified. These issues are important but are covered by other programmes of work at IRENA.

It is important to include clear definitions of the technology categories, where this is relevant, to ensure that cost comparisons are robust and provide useful insights (e.g. small hydro vs. large hydro, run-of-river vs. pumped hydro). It is also useful to identify any additional functionality and/or qualities of the renewable power generation technologies being investigated (e.g. the ability to store water for later generation and provide ancillary grid services). It is vital to ensure that system boundaries for costs are clearly set and that the available data are directly comparable.

The data used for the comparisons in this paper come from a variety of sources, such as business journals, industry associations, consultancies, governments, auctions and tenders. Every effort has been made to ensure that these data are directly comparable and are for the same system boundaries. Where this is not the case, the data have been corrected to a common basis using the best available data or assumptions. It is planned that these data will be complemented by detailed surveys of real world project data in forthcoming work by the Agency.

An important point is that, although this paper tries to examine costs, strictly speaking, the data available are actually prices, and not even true market average prices, but price indicators. The difference between costs and prices is determined by the amount above, or below, the normal profit that would be seen in a competitive market.

The cost of equipment at the factory gate is often available from market surveys or from other sources. A key difficulty is often reconciling different sources of data to identify why data for the same period differs. The balance of capital costs in total project costs

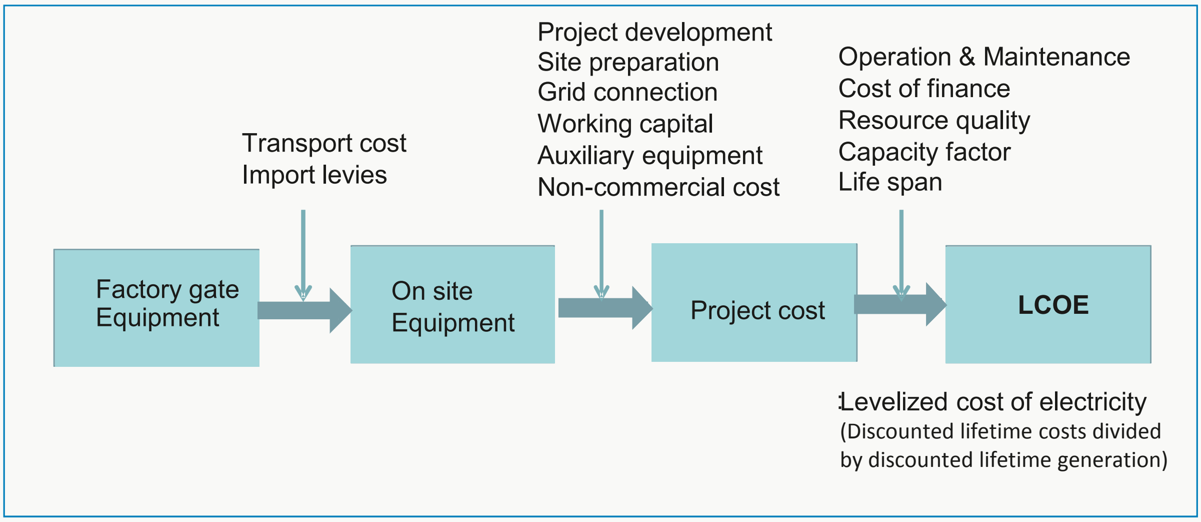

Figure 1.1: Renewable power generation cost indicators and boundaries

3 See EWEA, *Wind Energy and Electricity Prices,* April 2010 for a discussion

tends to vary even more widely than power generation equipment costs as it is often based on significant local content, which depends on the cost structure of where the project is being developed. Total installed costs can therefore vary significantly by project, country and region depending on a wide range of factors.

1.2 LEVELISED COST OF ELECTRICITY GENERATION

The LCOE of renewable energy technologies varies by technology, country and project based on the renewable energy resource, capital and operating costs, and the efficiency/performance of the technology. The approach used in the analysis presented here is based on a discounted cash flow (DCF) analysis. This method of calculating the cost of renewable energy technologies is based on discounting financial flows (annual, quarterly or monthly) over the project lifetime to a common basis, taking into consideration the time value of money. Given the capital-intensive nature of most renewable power generation technologies and the fact that fuel costs are low, or often zero, the weighted average cost of capital (WACC), often also referred to as the discount rate[4], used to evaluate the project has a critical impact on the LCOE.

There are many potential trade-offs to be considered when developing an LCOE modelling approach. The approach taken here is relatively simplistic, given the fact that the model needs to be applied to a wide range of technologies in different countries and regions. However, this has the additional advantage that the analysis is transparent and easy to understand. In addition, a more detailed LCOE analysis results in a significantly higher overhead in terms of the granularity of assumptions required. This often gives the impression of greater accuracy, but when it is not possible to robustly populate the model with assumptions, or to differentiate assumptions based on real world data, then the "accuracy" of the approach can be misleading.

The formula used for calculating the LCOE of renewable energy technologies is:

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where:

LCOE = the average lifetime levelised cost of electricity generation;
I_t = investment expenditures in the year **t**;
M_t = operations and maintenance expenditures in the year **t**;
F_t = fuel expenditures in the year **t**;
E_t = electricity generation in the year **t**;
r = discount rate; and
n = economic life of the system.

All costs presented in this paper are real 2010 USD, that is to say after inflation has been taken into account.[5] The LCOE is the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate. An electricity price above this would yield a greater return on capital, while a price below it would yielder a lower return on capital, or even a loss.

As already mentioned, although different cost measures are useful in different situations, the LCOE of renewable energy technologies is a widely used measure by which renewable energy technologies can be evaluated for modelling or policy development. Similarly, more detailed discounted cash flow approaches that take into account taxation, subsidies and other incentives will be used by renewable energy project developers to assess the profitability of real world projects.

4 These are not necessarily the same but in the analysis in this paper are assumed to be equivalent values.
5 An analysis based on nominal values with specific inflation assumptions for each of the cost components is beyond the scope of this analysis. Project developers will develop their own specific cash flow models to identify the profitability of a project from their perspective.

2. HYDROPOWER TECHNOLOGIES AND RESOURCES

2.1 INTRODUCTION

Hydropower is a renewable energy source based on the natural water cycle. Hydropower is the most mature, reliable and cost-effective renewable power generation technology available (Brown, 2011). Hydropower schemes often have significant flexibility in their design and can be designed to meet base-load demands with relatively high capacity factors, or have higher installed capacities and a lower capacity factor, but meet a much larger share of peak demand.

Hydropower is the largest renewable energy source, and it produces around 16 % of the world's electricity and over four-fifths of the world's renewable electricity. Currently, more than 25 countries in the world depend on hydropower for 90 % of their electricity supply (99.3 % in Norway), and 12 countries are 100 % reliant on hydro. Hydro produces the bulk of electricity in 65 countries and plays some role in more than 150 countries. Canada, China and the United States are the countries which have the largest hydropower generation capacity (IPCC, 2011; REN21, 2011; and IHA, 2011).

Hydropower is the most flexible source of power generation available and is capable of responding to demand fluctuations in minutes, delivering base-load power and, when a reservoir is present, storing electricity over weeks, months, seasons or even years (Brown, 2011 and IPCC, 2011). One key advantage of hydropower is its unrivalled "load following" capability (i.e. it can meet load fluctuations minute-by-minute). Although other plants, notably conventional thermal power plants, can respond to load fluctuations, their response times are not as fast and often are not as flexible over their full output band. In addition to grid flexibility and security services (spinning reserve), hydropower dams with large reservoir storage be used to store energy over time to meet system peaks or demand decoupled from inflows. Storage can be over days, weeks, months, seasons or even years depending on the size of the reservoir.

As a result of this flexibility, hydropower is an ideal complement to variable renewables as, when the sun shines or the wind blows, reservoir levels can be allowed to increase for a time when there is no wind or sunshine. Similarly, when large ramping up or down of supply is needed due to increases or decreases in solar or wind generation, hydro can meet these demands. Hydroelectric generating units are able to start up quickly and operate efficiently almost instantly, even when used only for one or two hours. This is in contrast to thermal plant where start-up can take several hours or more, during which time efficiency is significantly below design levels. In addition, hydropower plants can operate efficiently at partial loads, which is not the case for many thermal plants.[6] Reservoir and pumped storage hydropower can be used to reduce the frequency of start-ups and shutdowns of conventional thermal plants and maintain a balance between supply and demand, thereby reducing the load-following burden of thermal plants (Brown, 2011).

Hydropower is the only large-scale and cost-efficient storage technology available today. Despite promising developments in other energy storage technologies, hydropower is still the only technology offering economically viable large-scale storage. It is also a relatively efficient energy storage option.

6 *Although many modern gas-fired plants can operate within one or two percentage points of their design efficiency over a relatively wide load range, this is usually not the case for older plants and coal-fired plants. Start-stop operation at partial loads for short periods therefore implies low efficiencies, will often increase O&M costs and may prematurely shorten the life of some components.*

The system integration capabilities of hydropower are therefore particularly useful for allowing the large-scale large penetration of wind and other variable power sources (IEA, 2010c). Systems with significant shares of large-scale hydro with significant reservoir storage will therefore be able to integrate higher levels of variable renewables at low cost than systems without the benefit of hydropower.

Hydropower can serve as a power source for both large, centralized and small, isolated grids. Small hydropower can be a cost-competitive option for rural electrification for remote communities in developed and developing countries and can displace a significant proportion of diesel-fired generation. In developing countries, another advantage of hydropower technology is that it can have important multiplier effects by providing both energy and water supply services (e.g. flood control and irrigation), thus bringing social and economic benefits.

Hydropower is generally CO_2-free in operation,[7] but there are GHG emissions from the construction of hydropower schemes[8], from silting in the reservoirs and from the decomposition of organic material (predominantly an issue in tropical regions). Hydropower schemes can have an important spatial and visual footprint. One of the greatest challenges with the development of hydropower is ensuring that the design and construction of hydropower projects is truly sustainable. This means that, in addition to an economic assessment, proper social and environmental impact assessments must be conducted and if there are negative impacts on local populations, ecosystems and biodiversity, these issues need to be mitigated in the project plan. In the past, this is an area where hydropower has had a poor track record in some cases.

Some of the more important impacts that need to be considered and mitigated include changes in river flow regimes, water quality, changes in biodiversity, population displacement and the possible effects of dams on fish migration.[9]

Although hydropower technologies are mature, technological innovation and R&D into variable-speed generation technology, efficient tunnelling techniques, integrated river basin management, hydrokinetics, silt erosion resistant materials and environmental issues (e.g. fish-friendly turbines) will provide continuous improvement of environmental performance and, in many cases, costs reductions (IPCC, 2011).

2.2 HYDROPOWER TECHNOLOGIES

Hydropower has been used by mankind since ancient times. The energy of falling water was used by the Greeks to turn waterwheels that transferred their mechanical energy to a grinding stone to turn wheat into flour more than 2000 years ago. In the 1700s, mechanical hydropower was used extensively for milling and pumping.

The modern era of hydropower development began in 1870 when the first hydroelectric power plant was installed in Cragside, England. The commercial use of hydropower started in 1880 in Grand Rapids, Michigan, where a dynamo driven by a water turbine was used to provide theatre and store front lighting (IPCC, 2011). These early hydropower plants had small capacities by today's standards but pioneered the development of the modern hydropower industry.

Hydropower schemes range in size from just a few watts for pico-hydro to several GW or more for large-scale projects. Larger projects will usually contain a number of turbines, but smaller projects may rely on just one turbine. The two largest hydropower projects in the world are the 14 GW Itaipu project in Brazil and the Three Gorges project in China with 22.4 GW. These two projects alone produce 80 to 100 TWh/year (IPCC, 2011).

Large hydropower systems tend to be connected to centralised grids in order to ensure that there is enough demand to meet their generation capacity. Small hydropower plants can be, and often are, used in isolated areas off-grid or in mini-grids. In isolated grid systems, if large reservoirs are not possible, natural seasonal flow variations might require that hydropower plants be combined with other generation sources in order to ensure continuous supply during dry periods.

7 Hydropower projects account for an estimated half of all "certified emissions reduction" credits in the CDM pipeline for renewable energy projects (Branche, 2012).

8 These can be direct (e.g. CO_2 emissions from construction vehicles) or indirect (e.g. the CO_2 emissions from the production of cement).

9 The International Hydropower Association has a "hydropower sustainability assessment protocol" that enables the production of a sustainability profile for a project through the assessment of performance within important sustainability. www.hydropower.org.

Hydropower transforms the potential energy of a mass of water flowing in a river or stream with a certain vertical fall (termed the "head"[10]). The potential annual power generation of a hydropower project is proportional to the head and flow of water. Hydropower plants use a relatively simple concept to convert the energy potential of the flowing water to turn a turbine, which, in turn, provides the mechanical energy required to drive a generator and produce electricity (Figure 2.1).

The main components of a conventional hydropower plant are:

- *Dam*: Most hydropower plants rely on a dam that holds back water, creating a large water reservoir that can be used as storage. There may also be a de-silter to cope with sediment build-up behind the dam.
- *Intake, penstock and surge chamber:* Gates on the dam open and gravity conducts the water through the penstock (a cavity or pipeline) to the turbine. There is sometimes a head race before the penstock. A surge chamber or tank is used to reduce surges in water pressure that could potentially damage or lead to increased stresses on the turbine.
- *Turbine:* The water strikes the turbine blades and turns the turbine, which is attached to a generator by a shaft. There is a range of configurations possible with the generator above or next to the turbine. The most common type of turbine for hydropower plants in use today is the Francis Turbine, which allows a side-by-side configuration with the generator.
- *Generators:* As the turbine blades turn, the rotor inside the generator also turns and electric current is produced as magnets rotate inside the fixed-coil generator to produce alternating current (AC).

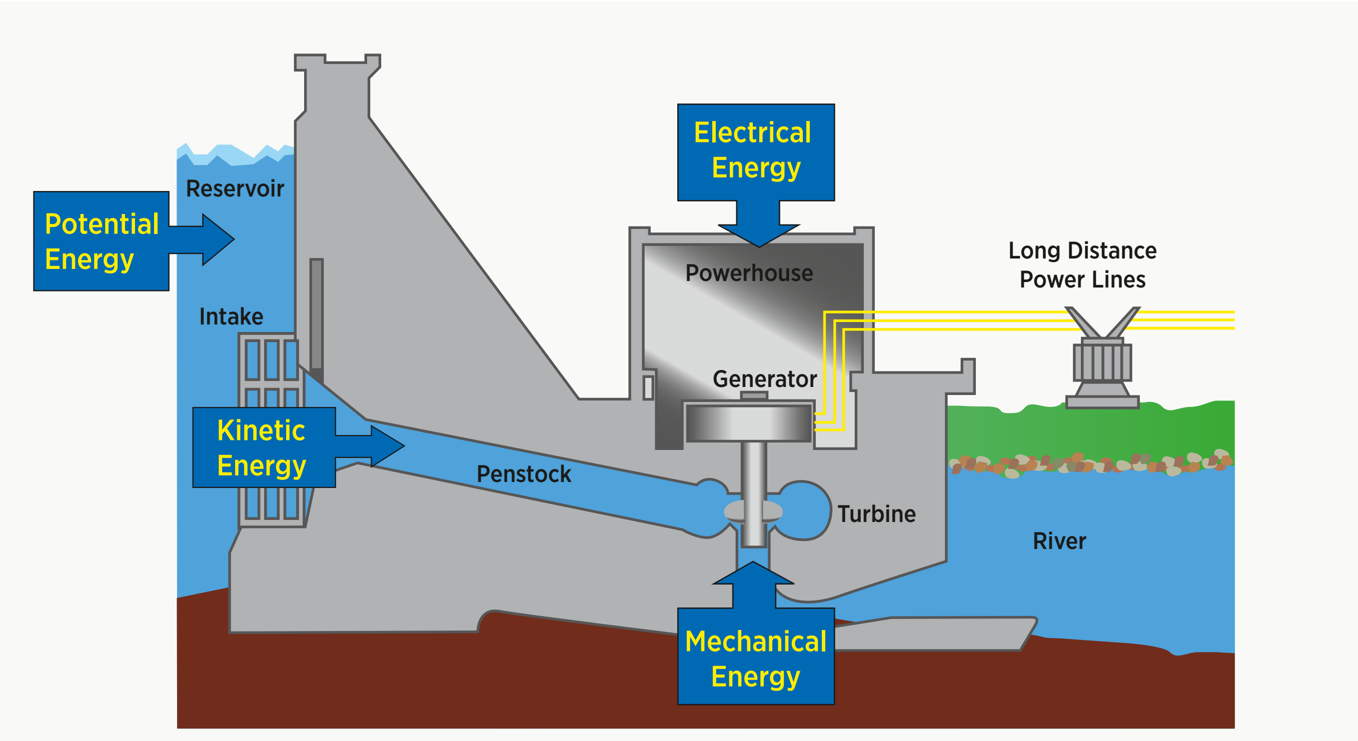

Figure 2.1: Typical "low head" hydropower plant with storage
(Picture adapted from Hydropower News and Information (http://www.alternative-energy-news.info/technology/hydro/)

10 *"Head" refers to the vertical height of the fall of a stream or river. Higher heads provide a greater pressure and therefore greater hydropower potential.*

» *Transformer*: The transformer inside the powerhouse takes the AC voltage and converts it into higher-voltage current for more efficient (lower losses) long-distance transport.

» *Transmission lines:* Send the electricity generated to a grid-connection point, or to a large industrial consumer directly, where the electricity is converted back to a lower-voltage current and fed into the distribution network. In remote areas, new transmission lines can represent a considerable planning hurdle and expense.

» *Outflow:* Finally, the used water is carried out through pipelines, called tailraces, and re-enters the river downstream. The outflow system may also include "spillways" which allow the water to bypass the generation system and be "spilled" in times of flood or very high inflows and reservoir levels.

Hydropower plants usually have very long lifetimes and, depending on the particular component, are in the range 30 to 80 years. There are many examples of hydropower plants that have been in operation for more than 100 years with regular upgrading of electrical and mechanical systems but no major upgrades of the most expensive civil structures (dams, tunnels) (IPCC, 2011).

The water used to drive hydropower turbines is not "consumed" but is returned to the river system. This may not be immediately in front of the dam and can be several kilometres or further downstream, with a not insignificant impact on the river system in that area. However, in many cases, a hydropower system can facilitate the use of the water for other purposes or provide other services such as irrigation, flood control and/or more stable drinking water supplies. It can also improve conditions for navigation, fishing, tourism or leisure activities.

The components of a hydropower project that require the most time and construction effort are the dam, water intake, head race, surge chamber, penstock, tailrace and powerhouse. The penstock conveys water under pressure to the turbine and can be made of, or lined with, steel, iron, plastics, concrete or wood. The penstock is sometimes created by tunnelling through rock, where it may be lined or unlined.

The powerhouse contains most of the mechanical and electrical equipment and is made of conventional building materials although in some cases this maybe underground. The primary mechanical and electrical components of a small hydropower plant are the turbines and generators.

Turbines are devices that convert the energy from falling water into rotating shaft power. There are two main turbine categories: "reactionary" and "impulse". Impulse turbines extract the energy from the momentum of the flowing water, as opposed to the weight of the water. Reaction turbines extract energy from the pressure of the water head.

The most suitable and efficient turbine for a hydropower project will depend on the site and hydropower scheme design, with the key considerations being the head and flow rate (Figure 2.2). The Francis turbine is a reactionary turbine and is the most widely used hydropower turbine in existence. Francis turbines are highly efficient and can be used for a wide range of head and flow rates. The Kaplan reactionary turbine was derived from the Francis turbine but allows efficient hydropower production at heads between 10 and 70 metres, much lower than for a Francis turbine. Impulse turbines such as Pelton, Turgo and cross-flow (sometimes referred to as Banki-Michell or Ossberger) are also available. The Pelton turbine is the most commonly used turbine with high heads. Banki-Michell or Ossberger turbines have lower efficiencies but are less dependent on discharge and have lower maintenance requirements.

There are two types of generators that can be used in small hydropower plants: asynchronous (induction)

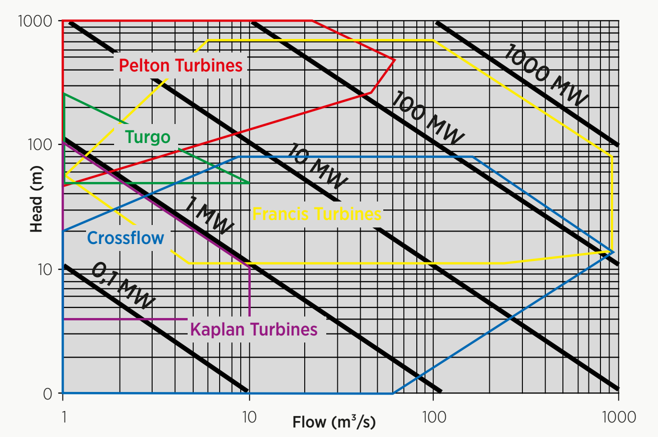

Figure 2.2: Working areas of different turbine types

Source: Based on NHA and HRF, 2010.

and synchronous machines (NHA and HRF, 2010). Asynchronous generators are generally used for micro-hydro projects.

Small hydropower, where a suitable site exists, is often a very cost-effective electric energy generation option. It will generally need to be located close to loads or existing transmission lines to make its exploitation economic. Small hydropower schemes typically take less time to construct than large-scale ones although planning and approval processes are often similar (Egre and Milewski, 2002).

Large-scale hydropower plants with storage can largely de-couple the timing of hydropower generation from variable river flows. Large storage reservoirs may be sufficient to buffer seasonal or multi-seasonal changes in river flows, whereas smaller reservoirs may be able to buffer river flows on a daily or weekly basis.

With a very large reservoir relative to the size of the hydropower plant (or very consistent river flows), hydropower plants can generate power at a near-constant level throughout the year (i.e. operate as a base-load plant). Alternatively, if the scheme is designed to have hydropower capacity that far exceeds the amount of reservoir storage, the hydropower plant is sometimes referred to as a peaking plant and is designed to be able to generate large quantities of electricity to meet peak electricity system demand. Where the site allows, these are design choices that will depend on the costs and likely revenue streams from different configurations.

2.3 HYDROPOWER CLASSIFICATION BY TYPE

Hydropower plants can be constructed in a variety of sizes and with different characteristics. In addition to the importance of the head and flow rate, hydropower schemes can be put into the following categories:[11]

- *Run-of-river* hydropower projects have no, or very little, storage capacity behind the dam and generation is dependent on the timing and size of river flows.

- *Reservoir* (storage) hydropower schemes have the ability to store water behind the dam in a reservoir in order to de-couple generation from hydro inflows. Reservoir capacities can be small or very large, depending on the characteristics of the site and the economics of dam construction.

- *Pumped storage* hydropower schemes use off-peak electricity to pump water from a reservoir located after the tailrace to the top of the reservoir, so that the pumped storage plant can generate at peak times and provide grid stability and flexibility services.

These three types of hydropower plants are the most common and can be developed across a broad spectrum of size and capacity from the very small to very large, depending on the hydrology and topography of the watershed. They can be grid-connected or form part of an isolated local network.

Run-of-river technologies

In run-of-river (ROR) hydropower systems (and reservoir systems), electricity production is driven by the natural flow and elevation drop of a river. Run-of-river schemes have little or no storage, although even run-of-river schemes without storage will sometimes have a dam.[12] Run-of-river hydropower plants with storage are said to have "pondage". This allows very short-term water storage (hourly or daily). Plants with pondage can regulate water flows to some extent and shift generation a few hours or more over the day to when it is most needed. A plant without pondage has no storage and therefore cannot schedule its production. The timing of generation from these schemes will depend on river flows. Where a dam is not used, a portion of the river water might be diverted to a channel or pipeline (penstock) to convey the water to the turbine.

11 *In addition to these established and mature hydropower technologies, so-called "in-stream" hydropower technologies allow the generation of electricity without disruption to the river system and cost of dam construction. In-stream hydropower technologies have yet to be deployed at scale and are beyond the scope of this report. However, R&D is progressing and they have a number of interesting features that mean that it is worth pursuing.*

12 *The definition of "run-of-river" hydropower projects varies around the world. A strict definition is that it is a system without storage, but in many countries this is applied to systems with several hours or even days of storage.*

Run-of-river schemes are often found downstream of reservoir projects as one reservoir can regulate the generation of one or many downstream run-of-river plant. The major advantage of this approach is that it can be less expensive than a series of reservoir dams because of the lower construction costs. However, in other cases, systems will be constrained to be run-of-river because a large reservoir at the site is not feasible.

The operation regime of run-of-river plants, with and without pondage, depends heavily on hydro inflows. Although it is difficult to generalise, some systems will have relatively stable inflows while others will experience wide variations in inflows. A drawback of these systems is that when inflows are high and the storage available is full, water will have to be "spilled". This represents a lost opportunity for generation and the plant design will have to trade off capacity size to take advantage of high inflows, with the average amount of time these high inflows occur in a normal year. The value of the electricity produced will determine what the trade-off between capacity and spilled water will be and this will be taken into account when the scheme is being designed.

Hydropower schemes with reservoirs for storage

Hydropower schemes with large reservoirs behind dams can store significant quantities of water and effectively act as an electricity storage system. As with other hydropower systems, the amount of electricity that is generated is determined by the volume of water flow and the amount of hydraulic head available.

The advantage of hydropower plants with storage is that generation can be decoupled from the timing of rainfall or glacial melt. For instance, in areas where snow melt provides the bulk of inflows, these can be stored through spring and summer to meet the higher electricity demand of winter in cold climate countries, or until summer to meet peak electricity demands for cooling. Hydropower schemes with large-scale reservoirs thus offer unparalleled flexibility to an electricity system.

The design of the hydropower plant and the type and size of reservoir that can be built are very much dependent on opportunities offered by the topography and are defined by the landscape of the plant site. However, improvements in civil engineering techniques that reduce costs mean that what is economic is not fixed. Reduced costs for tunnelling or canals can open up increased opportunities to generate electricity.

Hydropower can facilitate the low-cost integration of variable renewables into the grid, as it is able to respond almost instantaneously to changes in the amount of electricity running through the grid and to effectively store electricity generated by wind and solar by holding inflows in the reservoir rather than generating. This water can then be released when the sun is not shining or the wind not blowing. In Denmark, for example, the high level of variable wind generation (>20 % of the annual electricity production) is managed in part through interconnections to Norway where there is substantial hydropower storage (Nordel, 2008a).

Pumped storage hydropower technologies

Pumped hydro plants allow off-peak electricity to be used to pump water from a river or lower reservoir up to a higher reservoir to allow its release during peak times. Pumped storage plants are not energy sources but instead are storage devices. Although the losses of the pumping process contribute to the cost of storage, they are able to provide large-scale energy storage and can be a useful tool for providing grid stability services and integrating variable renewables, such as wind and solar.

Pumped storage and conventional hydropower with reservoir storage are the only large-scale, low-cost electricity storage options available today (Figure 2.3). Pumped storage represents about 2.2 % of all generation capacity in the United States, 18 % in Japan and 19 % in Austria (IEA, 2012 and Louis, 2012).

Pumped storage power plants are much less expensive than lead-acid and Li-ion batteries. However, an emerging solution for short-term storage are Sodium-Sulphur (NaS) batteries, but these are not as mature as pumped hydro and costs need to be confirmed (Figure 2.3). However, pumped storage plants are generally more expensive than conventional large hydropower schemes with storage, and it is often very difficult to find good sites to develop pumped hydro storage schemes.

Pumped hydropower systems can use electricity, not just at off-peak periods, but at other times where having some additional generation actually helps to reduce grid costs or improve system security. One example is where spinning reserve committed from thermal power plants

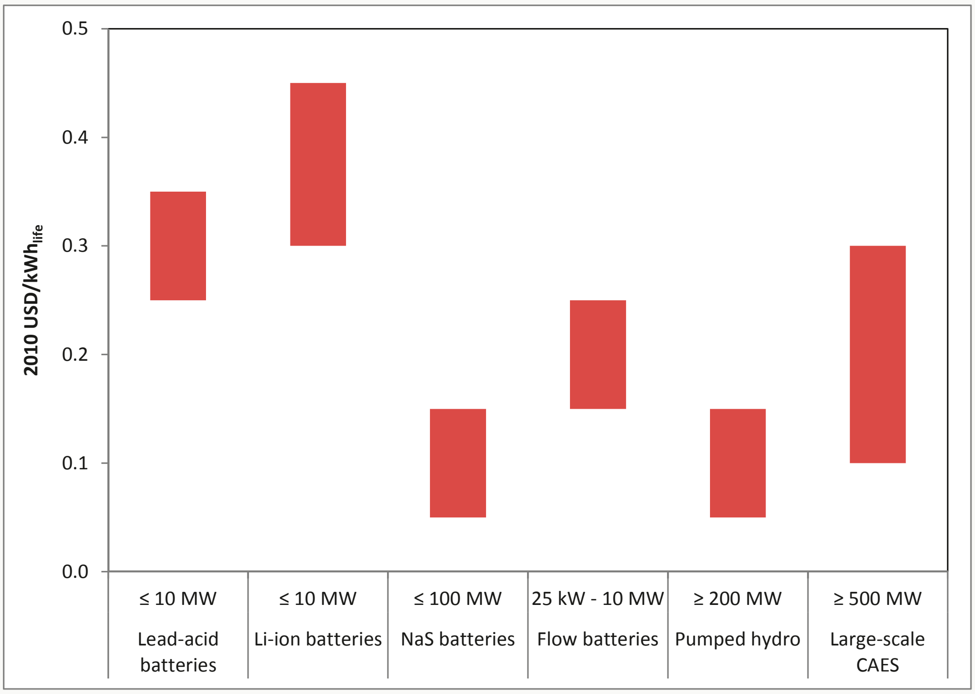

Figure 2.3: Comparison of the lifecycle cost of electricity storage systems

Source: IRENA, 2012.

would be at a level where they would operate at low, inefficient loads. Pumped hydro demand can allow them to generate in a more optimal load range, thus reducing the costs of providing spinning reserve. The benefits from pumped storage hydropower in the power system will depend on the overall mix of existing generating plants and the transmission network. However, its value will tend to increase as the penetration of variable renewables for electricity generation grows.

The potential for pumped storage is significant but not always located near demand centres. From a technical viewpoint, Norway alone has a long-term potential of 10 GW to 25 GW (35 TWh or more) and could almost double the present installed capacity of 29 GW (EURELECTRIC, 2011).

Hydropower capacity factors

The capacity factor achieved by hydropower projects needs to be looked at somewhat differently than for other renewable projects. For a given set of inflows into a catchment area, a hydropower scheme has considerable flexibility in the design process. One option is to have a high installed capacity and low capacity factor to provide electricity predominantly to meet peak demands and provide ancillary grid services. Alternatively, the installed capacity chosen can be lower and capacity factors higher, with potentially less flexibility in generation to meet peak demands and provide ancillary services.[13]

Analysis of data from CDM projects helps to emphasise this point. Data for 142 projects around the world yield capacity factors of between 23 % and 95 %. The average capacity factor was 50 % for these projects (Figure 2.4).

2.4 LARGE AND SMALL HYDROPOWER SCHEMES

A classification of hydropower by head is interesting because it is this that determines the water pressure on the turbines, which, together with discharge, are

13 This is a generalisation, and it is impossible to be categorical about this distinction as there is a continuum of possibilities over a year for each type of plant to provide all these services.

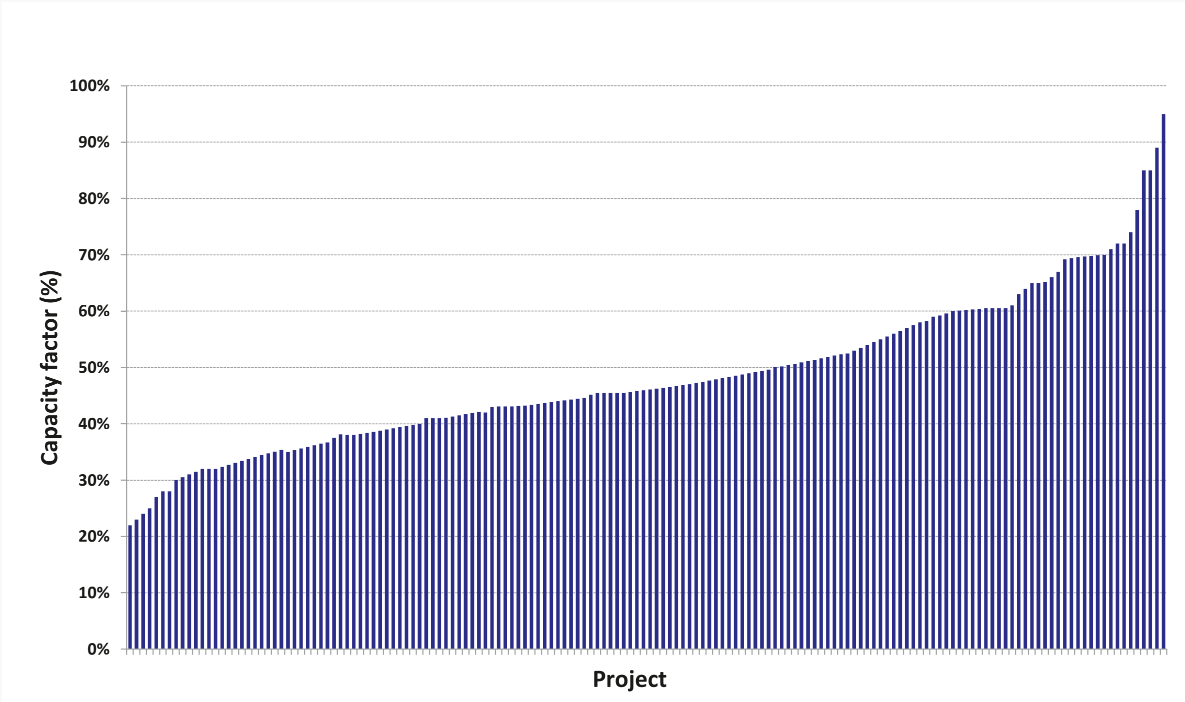

Figure 2.4: Capacity factors for hydropower projects in the Clean Development Mechanism

Source: Branche, 2011.

the most important parameters for deciding the type of hydraulic turbine to be used. However, generally speaking, hydro is usually classified by size (generating capacity) and the type of scheme (run-of-river, reservoir, pumped storage). Although there is no agreed definition, the following bands are typical to describe the size of hydropower projects:

» *Large-hydro*: 100 MW or more of capacity feeding into a large electricity grid;

» *Medium-hydro*: From 20 MW to 100 MW almost always feeding a grid;

» *Small-hydro*: From 1 MW to 20 MW usually feeding into a grid;

» *Mini-hydro*: From 100 kW to 1 MW that can be either stand-alone, mini-grid or grid-connected;

» *Micro-hydro*: From 5 kW to 100 kW that provide power for a small community or rural industry in remote areas away from the grid; and

» *Pico-hydro*: From a few hundred watts up to 5 kW (often used in remote areas away from the grid).

However, there is no agreed classification of "small" and "large" hydro and what constitutes "small" varies from country to country (Table 2.1). A given country's definition of what is a "small" hydropower system is often important because it can determine which schemes are covered by support policies for small hydro and which are covered by those (if any) for large hydro.

Table 2.1: Definition of small hydropower by country (MW)

	Small hydropower definition (MW)
Brazil	≤30
Canada	<50
China	≤50
European Union	≤20
India	≤25
Norway	≤10
Sweden	≤1.5
United States	5-100

Sources: IPCC, 2011 and IJHD, 2010.

Small hydropower plants are more likely to be run-of-river facilities than are large hydropower plants, but reservoir (storage) and run-of-river hydropower plants of all sizes utilise the same basic components and technologies.

The development of small hydropower plants for rural areas involves similar environmental, social, technical and economic considerations to those faced by large hydropower. Local management, ownership and community participation, technology transfer and capacity building are basic issues that will allow sustainable small hydropower plants to be developed. Small hydropower plants have been used to meet rural electrification goals in many countries. Currently there is 61 GW of small hydropower capacity in operation globally (Catanase and Phang, 2010). China has been particularly successful at installing small hydropower projects to meet rural electrification goals and 160 TWh was produced from 45 000 small hydro projects in China in 2010 (IN-SHP, 2010).

2.5 THE HYDROPOWER RESOURCE

The overall technical and economic potential for hydropower globally is available from some literature sources. However, the accuracy of these estimates is open to debate. In many cases country-level estimates of technical or economic potentials have been calculated using different criteria and combining these results means the totals are not directly comparable. Efforts to improve the mapping of the global hydropower resource are ongoing, but further work is required and should be encouraged.

However, taking into account these uncertainties, it is clear that the hydropower resource is very large, with many parts of the world being fortunate enough to have large resource potentials (Figure 2.4). Virtually all regions have some hydropower resources although these resources are sometimes concentrated in a small number of countries and are not always located adjacent to demand centres.

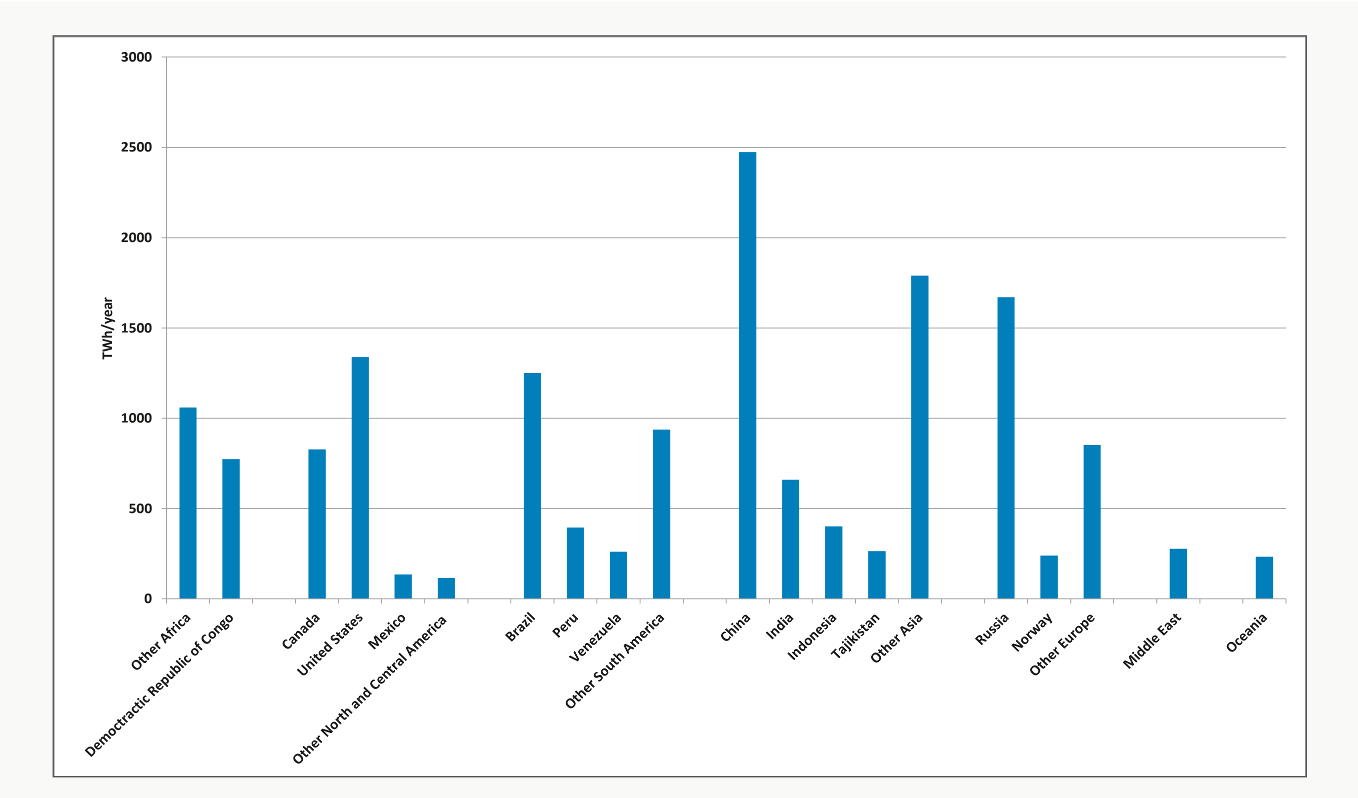

Figure 2.5: World hydropower technical resource potential[14] *Source: WEC, 2010.*

14 This is based on taking the theoretical total hydropower generation that could be achieved in a country by using all natural inflows as if they dropped to sea level and then assuming what proportion of this could technically be converted to hydropower with today's technologies. However, it is not known for certain whether all of the compiled data sources adhered to this methodology so the totals must be treated with caution.

Table 2.2: Hydropower resource potentials in selected countries

	Gross theoretical resource	Technically exploitable resource	Economically exploitable resource	Ratio of technical to economic
		(TWh)		
China	6 083	2 474	1 753	0.71
Russia	2 295	1 670	852	0.51
Brazil	3 040	1 250	818	0.65
Canada	2 067	827	536	0.65
India	2 638	660	442	0.67
United States	2 040	1 339	376	0.28
Tajikistan	527	264	264	1.00
Peru	1 577	395	260	0.66
Norway	600	240	206	0.86
Congo (Democratic Republic)	1 397	774	145	0.19
Venezuela	731	261	100	0.38
Indonesia	2 147	402	40	0.10
Mexico	430	135	33	0.24

Source: WEC, 2010.

The total technical hydropower resource potential depends on a number of critical assumptions in addition to average inflows into a catchment area. However, despite the uncertainty around the calculations, the estimated technical potential for hydropower is as much as 15 955 TWh/year or 4.8 times greater than today's production of hydropower. Estimates of the economically feasible hydropower capacity are not comprehensive enough to provide global estimates, but Table 2.2 presents data for a number of countries with important hydropower resources.

What the economically feasible hydropower potential is for a given country is a moving target. The cost of alternative generation options, which sets the limit at which the LCOE of a hydropower project would be economically feasible, as well as the costs of developing hydropower projects (e.g. through advances in civil engineering, cost reductions for equipment), will change over time. The simple analysis in Table 2.2 also highlights the limitations of some of the available data. The very high ratio of economic to technically feasible resources for some countries tends to suggest that only hydropower resources that have already been examined in detail have been included in the analysis. In other cases, the reason is that the country does have very economic hydropower resources.

Further work to better characterise the hydropower resource under standard definitions would help improve the comparability of resource estimates between countries and with other renewable power generation options. The efforts underway to achieve this should be encouraged.

Africa remains the region with the lowest ratio of deployment-to-potential, and the opportunities for growth are very large. However, in Africa complicated competing priorities and concerns mean that hydropower development is not straightforward.
The impact of hydropower development on local populations, their impacts on water use and rights, as well as issues over the biodiversity impacts of large-scale hydropower developments, mean that significant planning, consultation and project feasibility assessments are required. This is often required to take place in consultation with countries downstream, given the importance of Africa's rivers to the water supply of each country. Only once all major concerns are addressed can projects move to the detailed design phase and look to secure financing. The critical issue in Africa, and other regions, of the allocation of water rights between countries and different users within countries can be a significant delaying factor in getting project approval and funding. Growing populations and increasing water scarcity in some regions mean that these issues are complex and potentially divisive, but, without agreement, development is unlikely to move forward.

3. GLOBAL HYDROPOWER CAPACITY AND GENERATION TRENDS

3.1 CURRENT HYDROPOWER CAPACITY AND GENERATION

Hydropower is the largest source of renewable power generation worldwide. In 2009/2010 11 000 hydropower plants[15] in 150 countries were generating electricity. The total electricity generated by hydropower in 2009 reached 3 329 TWh, 16.5 % of global electricity production (Figure 3.1). This is around 85 % of total renewable electricity generation and provided more than one billion people with power (REN21, 2011 and IEA, 2011).

Global installed hydropower capacity was estimated to be between 926 GW and 956 GW in 2009/2010, excluding pumped storage hydropower capacity. Pumped hydro capacity was estimated to be between 120 GW and 150 GW (IHA, 2011) with a central estimate of 136 GW. In 2010, 30 GW of new hydro capacity was added (REN21, 2011 and BNEF, 2011). The global production of electricity from hydro was estimated to have increased by more than 5 % in 2010. This was driven by new capacity additions and above average hydro inflows in China (IHA, 2011). The world leaders in hydropower are China, Brazil, Canada, the United States and Russia. Together these countries account for 52 % of total installed capacity (Table 3.1)

Norway's generation system is almost 100 % hydro, with hydro accounting for 97 % of generation in 2009 and 99 % in 2010. In 2010, hydro accounted for 84 % of total generation in Brazil and 74 % in Venezuela. Central and South America generate nearly 64 % of all their electricity from hydropower (ANEEL, 2011). There are a number of countries in Africa that produce close to 100 % of their grid-based electricity from hydro. Russia has an

Table 3.1: Top ten countries by installed hydropower capacity and generation share, 2010

	Installed capacity (GW)		Hydropower's share of total generation (%)
China	210	Norway	99
Brazil	84	Brazil	84
USA	79	Venezuela	74
Canada	74	Canada	59
Russia	50	Sweden	49
India	38	Russia	19
Norway	30	India	18
Japan	28	China	16
France	21	Italy	14
Italy	20	France	8
Rest of world	302	Rest of world	14
World	936	World	16

Source: IHA, 2012 and IPCC, 2011.

15 These plants contained an estimated 27 000 generating units.

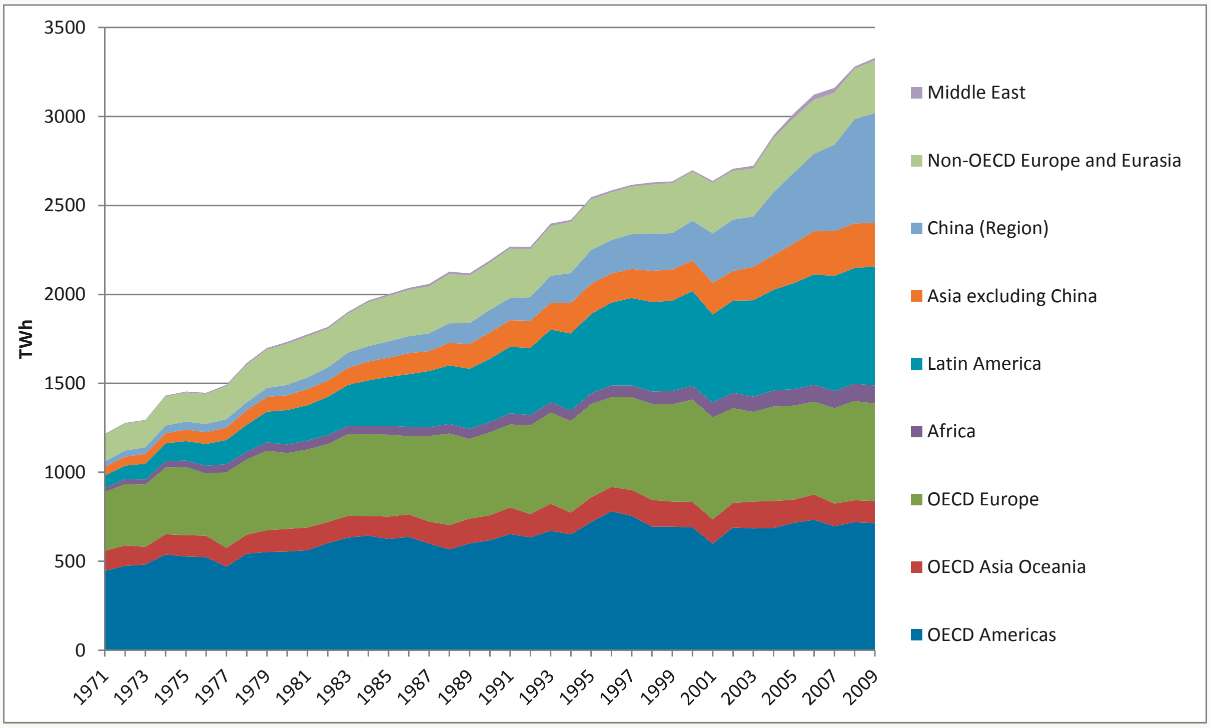

Figure 3.1: Hydropower generation by region, 1971 to 2009

Source: IEA.

estimated 50 to 55 GW of installed hydropower capacity, which represents about one-fifth of the country's total electric capacity (Frost and Sullivan, 2011).

Asia accounts for the largest share of global installed hydropower capacity, followed by Europe, then North and South America, then Africa (WEC, 2010 and IHA, 2011). China's installed hydropower capacity reached an estimated 210 GW in 2010, a significant increase over the 117 GW in operation at the end of 2005 (IHA, 2012 and US EIA, 2009). Despite having the largest installed capacity of hydropower plants in the world, only around 16% to 17% of China's total generation needs come from hydro. Hydropower in Africa currently accounts for some 32% of current capacity, but this capacity is just 3% to 7% of the technical potential on the continent (IRENA, 2011).

3.2 THE OUTLOOK FOR HYDROPOWER

With less than one-quarter of the world's technical hydropower potential in operation, the prospects for growth in hydro capacity are good. However, long lead times, project design, planning and approval processes, as well as the time required to secure financing for these large multi-year construction projects, mean that capacity growth is more likely to be slow and steady than rapid.

The conventional hydropower activities focus on adding new generating capacity, improving the efficiency/capacity at existing hydroelectric facilities, adding hydroelectric generating capacity to existing non-powered dams and increasing advanced pumped-storage hydropower capacity.

Emerging economies in Asia (led by China) and Latin America (led by Brazil) have become key markets for hydropower development, accounting for an estimated 60% of global activity (IHA, 2011). OECD economies in North America and Europe are focussing on the modernisation of existing facilities, often leading to increased capacity or generation capability, as well as new pumped storage facilities. However, new greenfield capacity is being added in relatively modest quantities.

China added 16 GW during 2010 to reach an estimated 210 GW of total hydro capacity. Brazil brought around 5 GW on stream in 2010, bringing its existing capacity to

81 GW while a further 8.9 GW is under construction (IHA, 2011 and IHA, 2012). In South America as a whole, 11 GW is planned and a further 16.3 GW is at the feasibility stage (IHA, 2012). In Western Asia, there is a total of 15.5 GW of capacity under construction with India accounting for 13.9 GW and Bhutan for 1.2 GW (IHA, 2012).

Canada added 500 MW of capacity in 2010, raising total installed hydropower capacity to 76 GW. However, the future should see higher rates of capacity coming on stream as more than 11 GW of new projects were under construction in Canada by early 2011. An estimated 1.3 GW of this is due to become operational before the end of 2012 (IHA, 2011 and REN 21, 2011). Canada has a total of 21.6 GW of hydropower capacity at different stages of planning or construction (IHA, 2012). Development in the United States has slowed recently due to the economic difficulties in North America. However, total installed capacity reached 78 GW in 2010 (to which must be added 20.5 GW of pumped storage), producing 257 TWh during the year, up from 233.6 TWh in 2009.

The largest projects completed in 2010 included the 1.1 GW Nam Theun 2 hydropower plant in Laos, China's 2.4 GW Jin'anqiao plant, Brazil's 0.9 GW Foz do Chapeco plant and two facilities (0.5 and 0.3 GW) in Ethiopia (IPCC, 2011).

Interest in pumped storage is increasing, particularly in regions and countries where solar PV and wind are reaching relatively high levels of penetration and/or are growing rapidly (IHA, 2011). The vast majority of current pumped storage capacity is located in Europe, Japan and the United States (IHA, 2011). About 4 GW of new pumped storage capacity was added globally in 2010, including facilities in China, Germany, Slovenia and the Ukraine. The central estimate of total pumped hydro capacity at the end of 2010 was approximately 136 GW, up from 98 GW in 2005 (IHA, 2011).

Worldwide, the installed capacity of small hydro is 61 GW (Catanase and Phang, 2010). Europe is a market leader in small hydropwoer technologies, and it is the second highest contributor to the European renewable energy mix. The European Commission's Renewable Energy Roadmap identifies small hydro power as an important ingredient in the EU's future energy mix.

China has ambitious plans that may not all be realised to start construction on 140 GW of capacity over the next five years (Reuters, 2011). In collaboration with Iran, China also plans to build the world's tallest dam, a 1.5 GW project in Iran's Zagros Mountains. Brazil plans two major projects in the Amazon region, including a 3.2 GW reservoir project due for completion in late 2011 (Hydro World, 2011). In North America and Europe, new plants are also under construction, but the focus is on modernising existing plants and adding pumped hydro storage capacity.

Long-term global scenarios for hydropower

A 2010 report from the International Energy Agency (IEA) projected that global hydropower production might grow by nearly 75% from 2007 to 2050 under a business-as-usual scenario, but that it could grow by roughly 85% over the same period in a scenario with aggressive action to reduce GHG emissions (IEA, 2010c). This is short of the IEA's assessment of the realistic potential for global hydropower, which is a two- to three-fold increase in generation over today's level. They estimate that the majority of the remaining economic development potential is located in Africa, Asia and Latin America (IEA, 2008 and IEA, 2010c). The IEA notes that, while small hydropower plants could provide as much as 150 GW to 200 GW of new generating capacity worldwide, only 5% of the world's small-scale hydropower potential has been exploited (IEA, 2008).

A review of the literature examining the potential contribution of renewable energy to climate change mitigation scenarios by the IPCC identified a median increase in the amount of hydropower generation of 35% by 2030 and 59% by 2050. However, the range of results in the scenarios examined was very wide, with the 25^{th} percentile of results indicating a 34% increase over 2009 by 2050, compared to a 100% increase for the 75^{th} percentile (IPCC, 2011).

4. THE CURRENT COST OF HYDROPOWER

Hydropower is a capital-intensive technology with long lead times for development and construction due to the significant feasibility, planning, design and civil engineering works required. There are two major cost components for hydropower projects:

- The civil works for the hydropower plant construction, including any infrastructure development required to access the site and the project development costs.
- The cost related to electro-mechanical equipment.

The project development costs include planning and feasibility assessments, environmental impact analysis, licensing, fish and wildlife/biodiversity mitigation measures, development of recreation amenities, historical and archaeological mitigation and water quality monitoring and mitigation.

The civil works costs can be broadly grouped into categories:

- Dam and reservoir construction;
- Tunnelling and canal construction;
- Powerhouse construction;
- Site access infrastructure;
- Grid connection;
- Engineering, procurement and construction (EPC); and
- Developer/owners costs (including planning, feasibility, permitting, etc.).

For developments that are far from existing transmission networks, the construction of transmission lines can contribute significantly to the total costs. Accessing remote sites may also necessitate the construction of roads and other infrastructure at the site.

The electro-mechanical equipment for the project includes the turbines, generators, transformers, cabling and control systems required. These costs tend to vary significantly less than the civil engineering costs, as the electro-mechanical equipment is a mature, well-defined technology, whose costs are not greatly influenced by the site characteristics. As a result, the variation in the installed costs per kW for a given hydropower project is almost exclusively determined by the local site considerations that determine the civil works needs.

There has been relatively little systematic collection of data on the historical trends of hydropower costs, at least in the publically available literature (IPCC, 2011). Such information could be compiled by studying the costs of the large number of already commissioned hydropower projects. However, because hydropower projects are so site-specific, it is difficult to identify trends. This would require detailed data on the cost breakdown of each project and require a significant investment in data collection, time and analysis. Until such time as analysis of this type is completed, it is therefore difficult to present historical trends in investment costs and the LCOE of hydropower.

4.1 TOTAL INSTALLED CAPITAL COSTS OF HYDROPOWER

The total investment costs for hydropower vary significantly depending on the site, design choices and the cost of local labour and materials. The large civil works required for hydropower mean that the cost of materials and labour plays a larger role in overall costs than for some other renewable technologies. There is significantly less variation in the electro-mechanical costs.

The total installed costs for large-scale hydropower projects typically range from a low of USD 1 000/kW to around USD 3 500/kW. However, it is not unusual to find projects with costs outside this range. For instance, installing hydropower capacity at an existing dam that was built for other purposes (flood control, water provision, etc.) may have costs as low as USD 500/kW. On the other hand, projects at remote sites, without adequate local infrastructure and located far from existing transmission networks, can cost significantly more than USD 3 500/kW.

Figure 4.1 summarises a number of studies that have analysed the costs of hydropower plants. A large, comprehensive cost analysis of over 2 155 potential hydropower projects in the United States totalling 43 GW identified an average capital cost of USD 1 650/kW, with 90 % of projects having costs below USD 3 350/kW (Hall, *et al.*, 2003). In another study (Lako et al., 2003), 250 projects worldwide with a total capacity of 202 GW had an average investment cost of just USD 1 000/kW and 90 % had costs of USD 1 700/kW or less (Lako et al., 2003).

Figure 4.2 presents the investment costs of hydropower projects by country. The cost of hydropower varies within countries and between countries depending on the resource available, site-specific considerations, cost structure of the local economy, etc., which explains the wide cost bands for hydropower. The lowest investment costs are typically associated with adding capacity at existing hydropower schemes or capturing energy from existing dams that do not have any hydropower facilities. The development of greenfield sites tends to be more expensive and typically range from USD 1 000 to USD 3 500/kW.

Small projects have investment costs in slightly higher range bands and are expected to have higher average costs. This is particularly true for plants with capacities of less than one MW where the specific (per kW) electro-mechanical costs can be very high and dominate total installed costs.

The investment costs per kW of small hydropower plant projects tend to be lower if the plant has higher head and installed capacity. The relationship between installed capacity and specific investment costs is strong irrespective of the head size. The economies of scale for head sizes above 25 to 30 metres are modest (Figure 4.3).

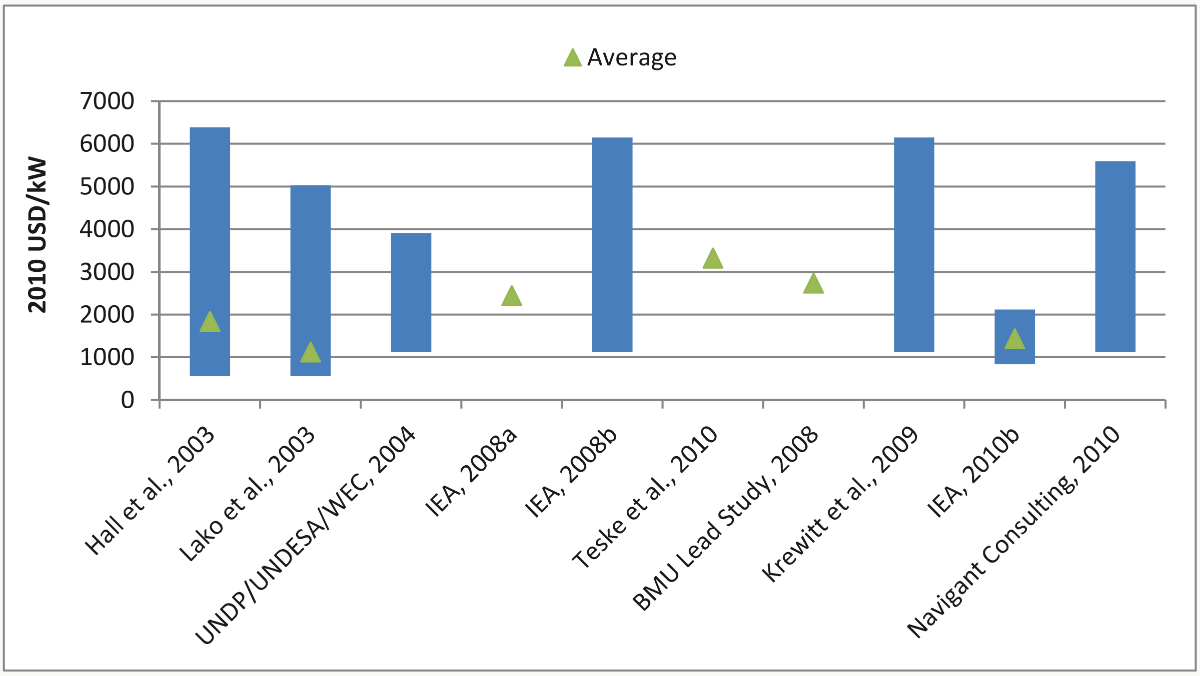

Figure 4.1: Summary of the installed costs hydropower projects from a range of studies

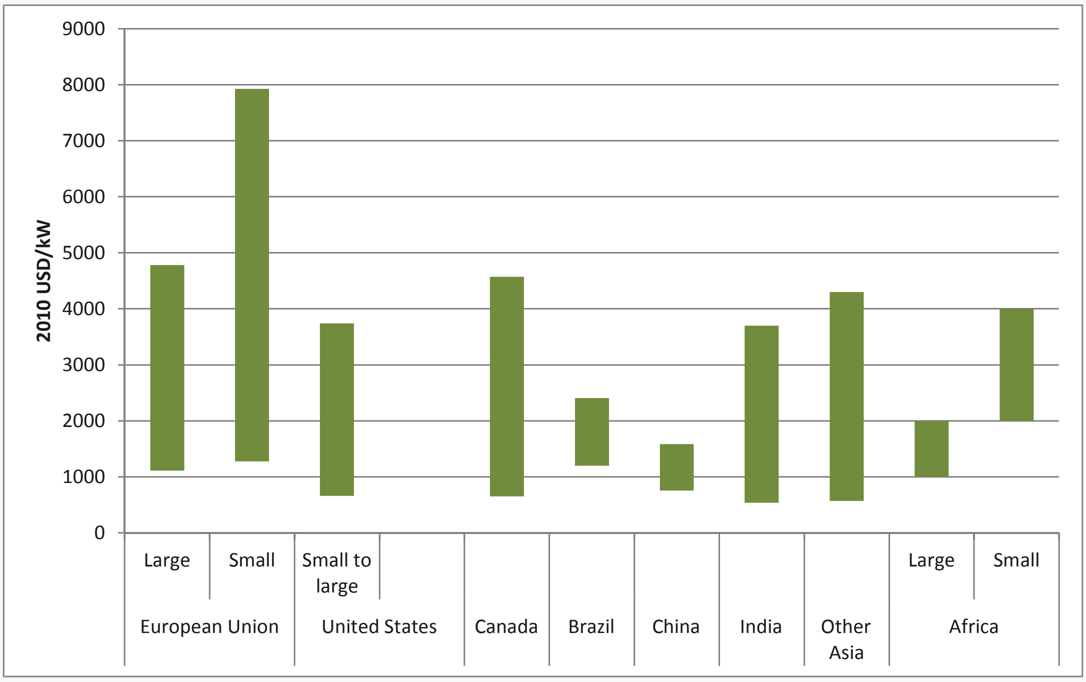

Figure 4.2: Total installed hydropower cost ranges by country

Sources: IRENA, 2011; IEA, 2010b; Black & Veatch, 2012; and IRENA/GIZ.

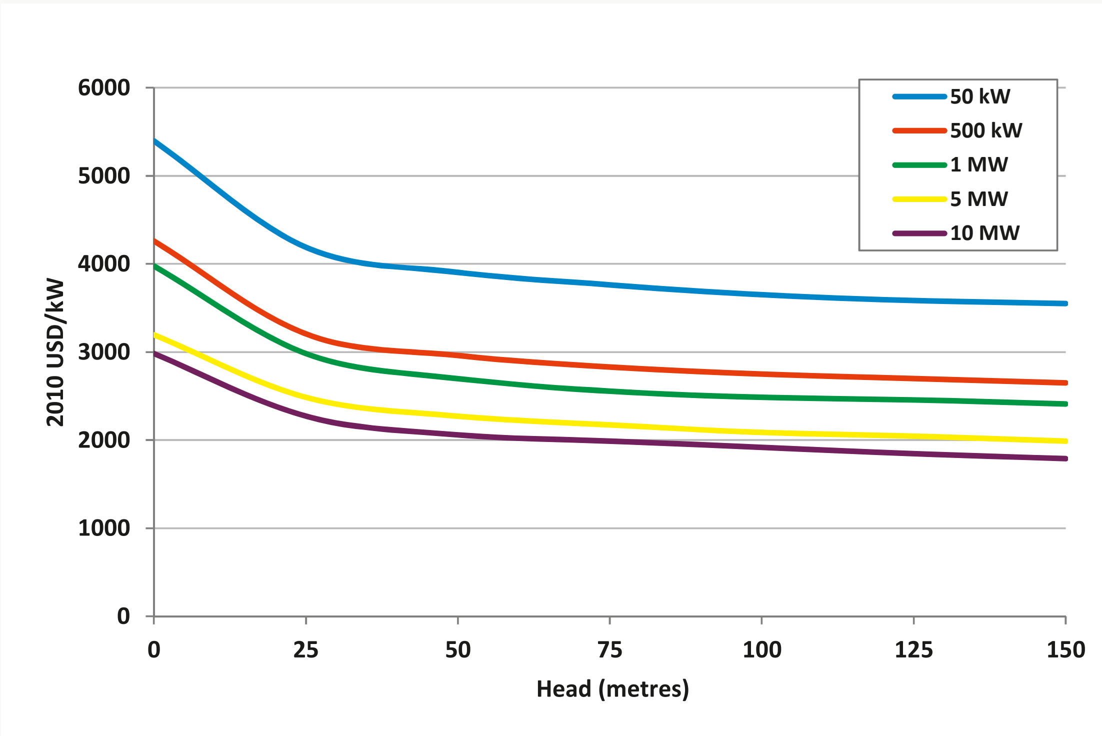

Figure 4.3: Investment costs as a function of installed capacity and turbine head

Source: Based on Kaldellis and Kondili, 2005.

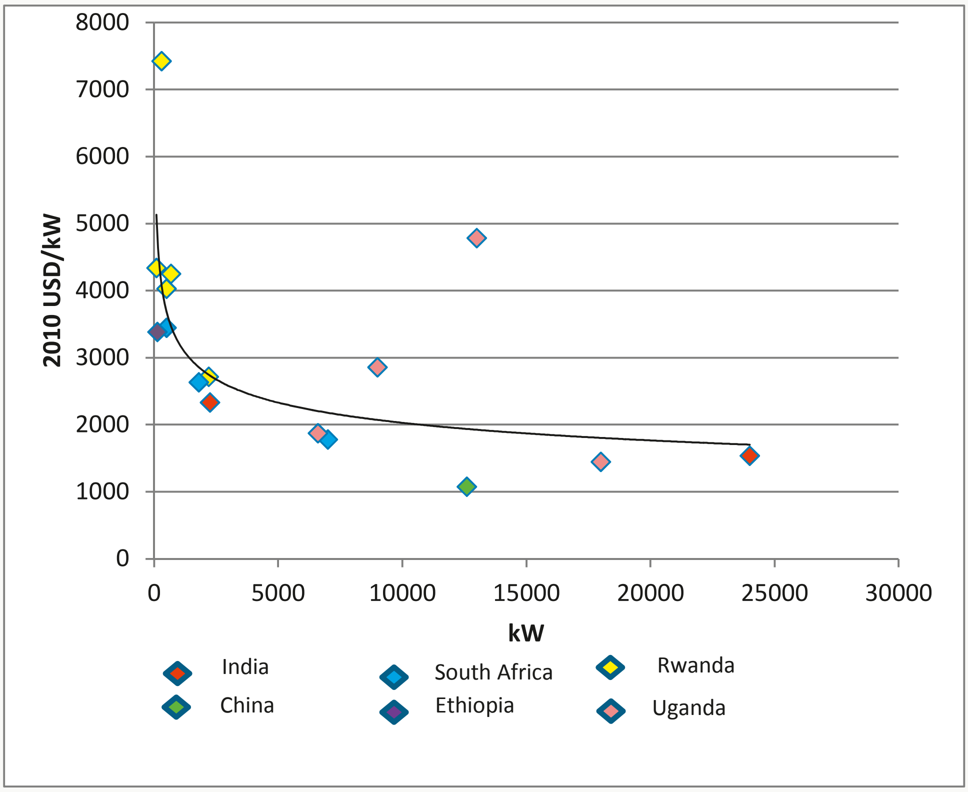

FIGURE 4.4: INSTALLED CAPITAL COSTS FOR SMALL HYDRO IN DEVELOPING COUNTRIES BY CAPACITY

Source: IRENA/GIZ.

In the United Kingdom, plants between 1 MW and 7 MW have installed capital capital costs between USD 3 400 and USD 4 000/kW (Crompton, 2010). However, plants below 1 MW can have significantly higher capital costs. The range can be from USD 3 400 to USD 10 000/kW, or even more for pico-hydropower projects.

Data for small hydro in developing countries from an IRENA/GIZ survey and from other sources highlight similar cost bands (Figure 4.4), although they suggest that larger small hydro projects in developing countries may have slightly lower specific costs. Critically, mini- and pico-hydro projects still appear to generally have costs below those of PV systems, suggesting that small hydros' role in off-grid electrification will remain a strong one.

For large hydropower plants, economic lifetimes are at least 40 years, and 80-year lifetimes can be used as upper bound. For small-scale hydropower plants, the typical lifetime is 40 years but in some cases can be less. The economic design lifetime may differ from actual physical plant lifetimes.

Refurbishment, repowering and rehabilitation of existing hydropower plants

Hydropower plant refurbishment, repowering and rehabilitation (hereafter referred to as "refurbishment" for simplicity) refer to a range of activities such as repair or replacement of components, upgrading generating capability and altering water management capabilities. Most refurbishment projects focus on the electro-mechanical equipment, but can involve repairs or redesigns of intakes, penstocks and tail races.

Generally speaking, the output of a hydropower scheme will decline over time as equipment and some of the civil works become worn down by the flow of water or constant use. At a certain point, it will often become economic to refurbish the plant to reduce the increasing O&M costs and restore generation capacity to its designed level, or even take the opportunity to boost it above this original level.

Refurbishment projects generally fall into two categories:

- *Life extension* is where equipment is replaced on a "like for like" basis and little effort is made to boost generating capacity potential from what it was. This will, however, generally result in increased generation relative to what was being produced at the scheme as worn out equipment is replaced. On average, these repairs will yield a 2.5 % gain in capacity; and

- *Upgrades* are where increased capacity and, potentially, efficiencies are incorporated into the refurbishment, where the increased cost can be justified by increased revenues. These upgrades can be modest or more extensive in nature and depending on the extent of the wear and tear and additional civil works to try and capture more energy yield increases in capacity of between 10 % and as much as 30 %.

The slowing in the development of greenfield projects in countries that have exploited most of their existing potential and the many countries with ageing hydropower projects mean that refurbishment will become an increasingly important way of boosting hydropower output and adding new capacity.

The rehabilitation and refurbishment of old hydropower plants will usually become economic at a certain point, as the reduced O&M costs and higher output post-refurbishment will offset what are the relatively modest low investment costs for refurbishment. In addition, the current R&D efforts into rehabilitation and refurbishment of hydropower plants include the development of innovative technologies to minimise their environmental impact.

For small hydropower plant, ambitious refurbishments can be envisaged. It may be possible to completely rebuild the hydropower scheme by constructing a new plant, completely replacing the main components and structures to capture more energy. The refurbishment of large hydropower schemes will generally aim to extend the plant's working lifespan, improve the yield, increase in reliability, reduce maintenance needs and increase the degree of automation of operations.

The key items that need to be replaced or repaired are the turbines, which can suffer from pitting, wear or even fatigue cracks. Similarly, in the generator, stator windings last for as much as 45 years, but will eventually benefit from replacement. The generator rotor and bearings could also need replacement. In addition to the electro-mechanical components, repairs or redesigns of intakes, penstocks and the other civil works can be considered in order to improve efficiency and increase electricity generation.

The data available on the costs of refurbishment isn't extensive, however, studies of the costs of life extension and upgrades for existing hydropower have estimated that life extensions cost around 60 % of greenfield electro-mechanical costs and upgrades anywhere up to 90 % depending on their extent (Goldberg and Lier, 2011).

4.2 BREAKDOWN OF HYDROPOWER COSTS BY SOURCE

The cost breakdown of an indicative 500 MW new greenfield hydropower project in the United States is presented in Figure 4.5. The reservoir accounts for just over one-quarter of the total costs, while tunnelling adds another 14 %. The powerhouse, shafts and electro-mechanical equipment together account for 30 % of the total costs. The long lead times for these types of hydropower projects (7-9 years) mean that owner costs (including the project development costs) can be a significant portion of the overall costs.

The largest share of installed costs for large hydropower plant is typically taken up by civil works for the construction of the hydropower plant (such us dam, tunnels, canal and construction of powerhouse, etc.). Electrical and mechanical equipment usually contributes less to the cost. However, for hydropower projects where the installed capacity is less than 5 MW, the costs of electro-mechanical equipment may dominate total costs due to the high specific costs of small-scale equipment.

The cost breakdown for small hydro projects in developing countries reflects the diversity of hydropower projects and their site-specific constraints and opportunities (Figure 4.6). The electro-mechanical equipment costs tend to be higher than for large-scale projects, contributing from 18 % to as much as 50 % of

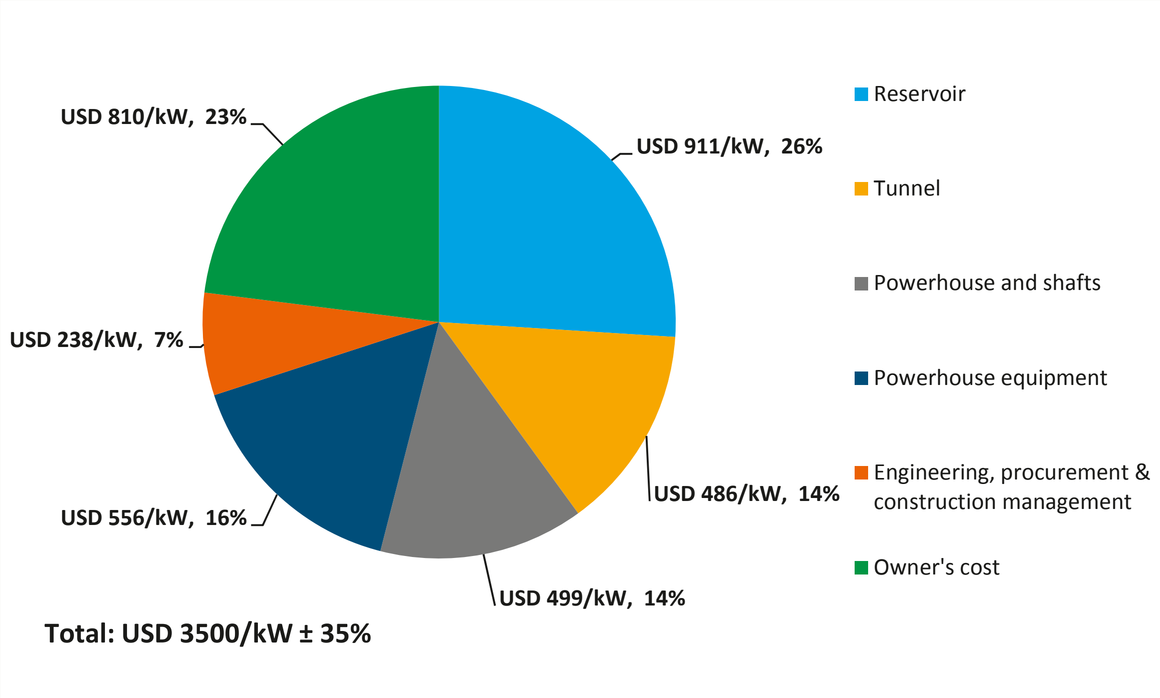

FIGURE 4.5: COST BREAKDOWN OF AN INDICATIVE 500 MW GREENFIELD HYDROPOWER PROJECT IN THE UNITED STATES

Source: Black and Veatch, 2012.

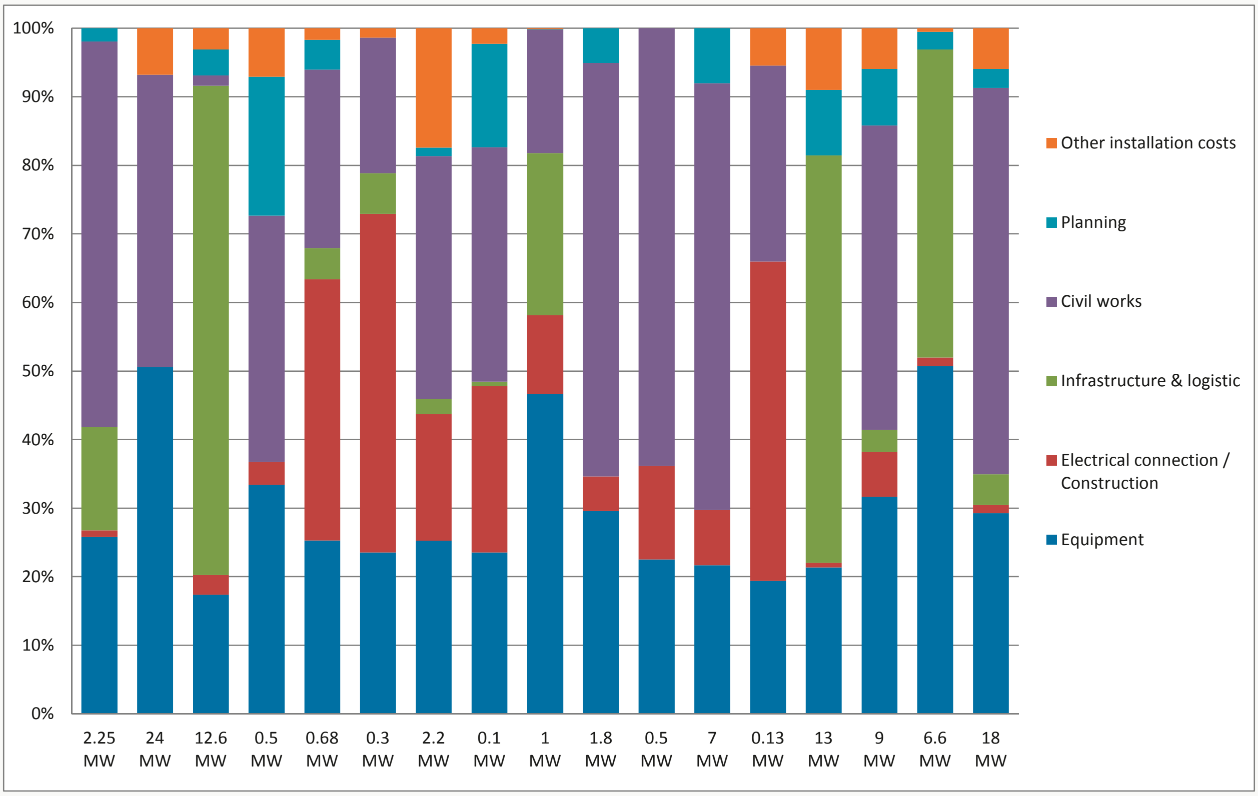

FIGURE 4.6: COST BREAKDOWN FOR SMALL HYDRO PROJECTS IN DEVELOPING COUNTRIES

Source: IRENA/GIZ.

total costs. For projects in remote or difficult to access locations, infrastructure costs can dominate total costs.

The contribution of civil works to capital costs

For large hydropower projects, the capital costs are dominated by the civil works. The cost of civil works is influenced by numerous factors pertaining to the site, the scale of development and the technological solution that is most economic. Hydropower is a highly site-specific technology where each project is a tailor-made outcome for a particular location within a given river basin to meet specific needs for energy and water management.

Around three-quarters of the total investment costs of hydropower projects are driven by site-specific elements that impact the civil engineering design and costs. Proper site selection and hydro scheme design are therefore key challenges (Ecofys, *et al.*, 2011). Therefore, proper dimensioning and optimisation of the key elements of civil structures and streamlining construction work during the engineering design and implementation stages are important factors to reduce construction costs of large-scale projects.

The site-specific factors that influence the civil construction costs include hydrological characteristics, site accessibility, land topography, geological conditions, the construction and design of the hydropower plant and the distance from existing infrastructure and transmission lines. The cost of the civil works for the hydropower plant will also depend on commodity prices and labour costs in the country. The cost of civil works in developing countries is sometimes lower than in developed countries due to the use of local labour. However, this is not always the case as poorer infrastructure or remote sites will entail significant additional costs. Similarly, cement and steel prices are sometimes higher in developing countries.

Electro-mechanical equipment costs

The electro-mechanical equipment used in hydropower plants is a mature technology, and the cost is strongly correlated with the capacity of the hydropower plant.

The proposed capacity of a hydropower plant can be achieved by using a combination of a few large turbines or many small turbines and generating units. This will be influenced to some extent by the hydro resource but is also a trade-off between guaranteeing availability (if there is only one generator and it is offline, then generation drops to zero) and the capital costs (smaller units can have higher costs per kW). The design decision is therefore a compromise between trying to minimise capital costs and maximise efficiency and the number of generating units to ensure the best availability.

A range of studies have analysed the cost of the electro-mechanical equipment for hydro plants as a function of total plant size and head.[16] Recent work has looked at using the following formula to describe the relationship between costs and the power and head of a small hydropower scheme (Ogayar and Vidal, 2009):

$$\text{COST (per kW)} = \alpha P^{1-\beta} H^{\beta 1}$$

Where:

P is the power in kW of the turbines;

H is the head in metres;

α is a constant; and

β and $\beta 1$ are the co-efficients for power and head, respectively.

The results from analysis using this cost estimation methodology is available for a range of developed countries, but most of these studies are ten years old or more. The recent analysis of small hydropower plants in Spain which analysed separately the costs for Pelton, Francis, Kaplan, and semi-Kaplan turbines yielded equations a good fit (Ogayar and Vidal, 2009).

The results yielded by these types of analysis have been checked against existing cost data for electro-mechanical equipment from global manufacturers (Alstom, Andritz, Gilbert Gilkes & Gordon Ltd, NHT and Voith Siemens) and were found to be statistically consistent with real cost data from existing plants. Although this type of analytical

16 See Ogayar and Vidal (2009) for some of these studies.

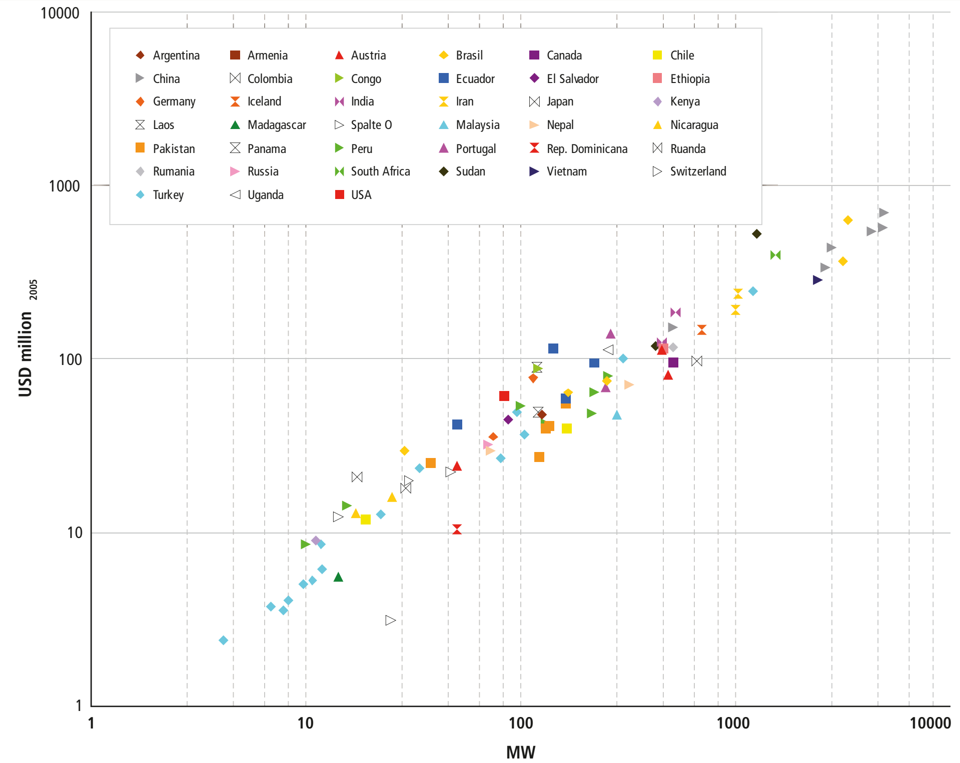

Figure 4.7: Electro-mechanical equipment for hydro as a function capacity by country (log-scale)

Source: Alvarado-Ancieta, 2009.

approach is a useful first order estimate of costs, the results need to be treated with caution, given the range of costs experienced in the real world (Figure 4.7).

4.3 OPERATION AND MAINTENANCE COSTS

Once commissioned, hydropower plants usually require little maintenance, and operation costs will be low. When a series of plants are installed along a river, centralised control and can reduce O&M costs to very low levels.

Annual O&M costs are often quoted as a percentage of the investment cost per kW per year. Typical values range from 1% to 4%. The IEA assumes 2.2% for large hydropower and 2.2% to 3% for smaller projects, with a global average of around 2.5% (IEA, 2010c). Other studies (EREC/Greenpeace, 2010 and Krewitt, 2009) indicate that fixed O&M costs represent 4% of the total capital cost. This figure may be appropriate for small-scale hydropower, but large hydropower plants will have values significantly lower than this. An average value for O&M costs of 2% to 2.5% is considered the norm for large-scale projects (IPCC, 2011 and Branche, 2012). This will usually include the refurbishment of mechanical and electrical equipment like turbine overhaul, generator rewinding and reinvestments in communication and control systems.

However, it does not cover the replacement of major electro-mechanical equipment or refurbishment of penstocks, tailraces, etc. The advantage of hydropower is that these kinds of replacements are infrequent and design lives of 30 years or more for the electro-mechanical equipment and 50 years or more for the refurbishment of penstocks and tail races are normal.

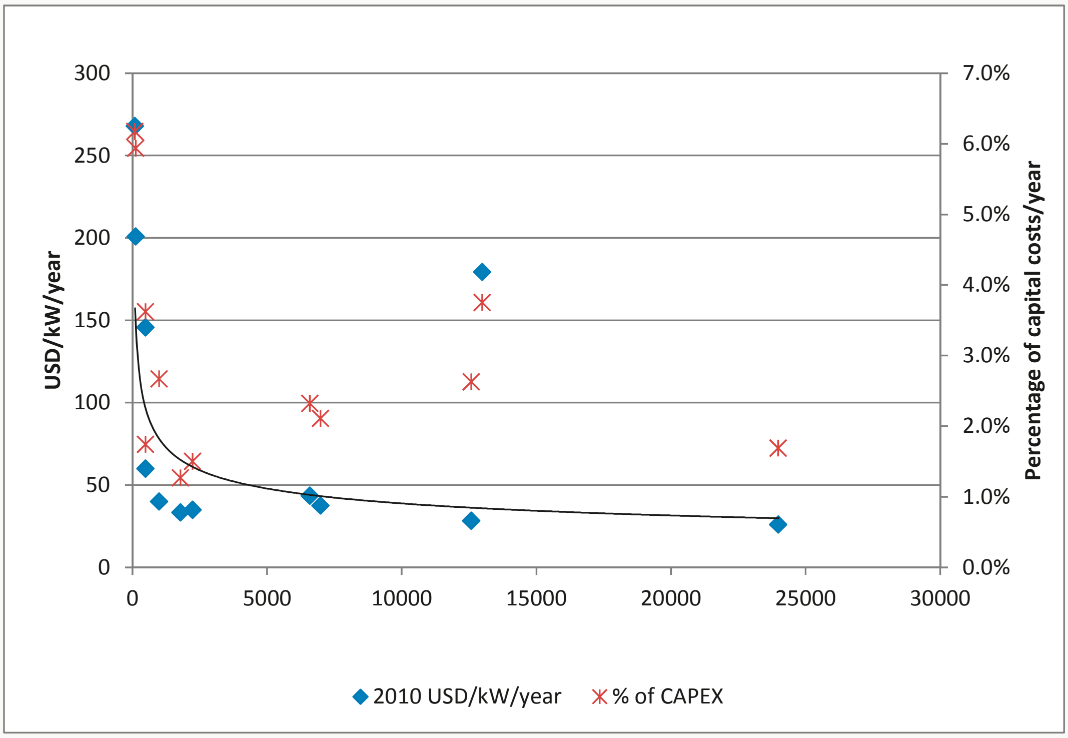

Figure 4.8: Operations and maintenance costs for small hydro in developing countries

Source: IRENA/GIZ.

A recent study indicated that O&M costs averaged USD 45/kW/year for large-scale hydropower projects and around USD 52/kW/year for small-scale hydropower plants (Ecofys et al., 2011). These figures are not inconsistent with the earlier analyses.

These values are consistent with data collected by IRENA and GIZ for small hydropower projects in developing countries (Figure 4.8). Average O&M costs for mini- and pico-hydro projects can be significantly above the average, given the economies of scale available for O&M costs at hydropower projects.

5. COST REDUCTION POTENTIALS

Hydropower is a mature, commercially proven technology and there is little scope for significant cost reductions in the short-to-medium term. Technological innovation could lower the costs in the future, although this will mainly be driven by the development of more efficient, lower cost techniques in civil engineering and works. These improvements and cost reductions in major civil engineering techniques (tunnelling, construction, etc.) could help to reduce hydropower investment costs below what they otherwise would be.

However, analysis of cost reduction potentials in the literature does not provide a clear picture of any likely trends. Some studies expect slight increases in the range of installed costs, while others expect slight decreases when looking out to 2030 or 2050 (EREC/ Greenpeace, 2010; IEA, 2008a; IEA, 2008b; IEA, 2010c; and Krewitt et al., 2009). Part of the problem is that it is difficult to separate out improvements in civil engineering techniques that may reduce costs (which would lower the supply curve) and the fact that the best and cheapest hydropower sites have typically already been exploited (i.e. we are moving up and along the supply curve). As a consequence of these difficulties, the inconclusive evidence from the literature and the fact that hydropower is a mature technology; no material cost reductions for hydropower are assumed in the period to 2020 in the analysis presented in this paper.

6. THE LEVELISED COST OF ELECTRICITY FROM HYDROPOWER

Hydropower is a proven, mature, predictable technology and can also be low-cost. It requires relatively high initial investments but has the longest lifetime of any generation plant (with parts replacement) and, in general, low operation and maintenance costs. Investment costs are highly dependent on the location and site conditions, which determine on average three-quarters of the development cost (Ecofys, *et al.*, 2011). The levelised cost of electricity for hydropower plants spans a wide range, depending on the project, but under good conditions hydropower projects can be very competitive.

Existing hydropower plants are some of the least expensive sources of power generation today (IEA, 2010b). However, there is a wide range of capital costs and capacity factors that are possible, such that the LCOE of hydropower is very site-specific. The critical assumptions required to calculate the LCOE of hydropower are the:

- Installed capital cost;
- Capacity factor;
- Economic life;
- O&M costs; and
- The cost of capital.

The cost of capital (discount rate) assumed to calculate the LCOE is 10 %.[17] The other assumptions have been sourced from the earlier sections of this paper.

There is insufficient information on the LCOE trends for hydropower, in part due to the very site-specific nature of hydropower projects and the lack of time series data on investment costs. Investment costs vary widely from a low of USD 450/kW to as much as USD 6 000/kW or more. Another complicating factor is that it is possible to design hydropower projects to perform very differently. Capacity can be low to ensure high average capacity factors, but at the expense of being able to ramp up production to meet peak demand loads. Alternatively, a scheme could have relatively high capacity and low capacity factors, if it is designed to help meet peak demands and provide spinning reserve and or/or other ancillary grid services.

The decision about which strategy to pursue for any given hydropower scheme is highly dependent on the local market, structure of the power generation pool, grid capacity/constraints, the value of providing grid services, etc. More than perhaps any other renewable energy, the true economics of a given hydropower scheme will be driven by these factors, not just the amount of kWh's generated relative to the investment. Hydropower is uniquely placed to capture peak power prices and the value of ancillary grid services, and these revenues can have a large impact on the economics of a hydropower project.[18]

6.1 RESULTS FROM STUDIES OF THE LCOE OF HYDROPOWER

Black & Veatch studied the cost of new renewable electricity generation in the western United States

17 This discount rate is the same as used in the four other renewable power generation costing papers on wind, biomass, solar PV and concentrating solar power.

18 It is beyond the scope of this report to try to quantify these benefits, but these are thought to add anywhere between USD 0.01 and USD 0.05/kWh in value, and, in certain cases, it could be even more.

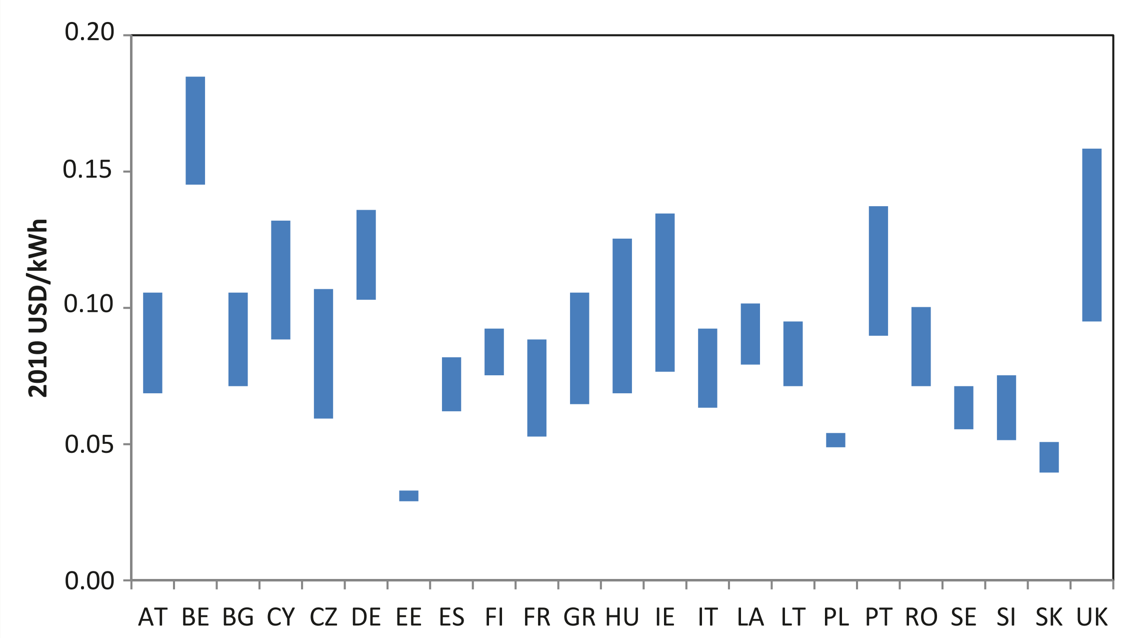

FIGURE 6.1: THE MINIMUM TO AVERAGE LEVELISED COST OF ELECTRICITY FOR SMALL HYDROPOWER IN THE EUROPEAN UNION
NOTE: COUNTRY ABBREVIATIONS ARE THE EU STANDARD.[19]

Source: Ecofys, et al., 2011.

(where much of the potential for new hydropower in the United States is located) and estimated that the LCOE of new hydropower capacity was in the range of USD 0.02/kWh to USD 0.085/kWh, with the lowest costs being for additional capacity at existing hydropower schemes (Pletka and Finn, 2009). This compares with earlier analysis that put the cost range at USD 0.018 to USD 0.13/kWh for new capacity at existing hydroelectric schemes and between USD 0.017 and USD 0.20/kWh for new greenfield hydropower schemes (WGA, 2009).

The LCOE of small hydropower in Europe, where most of the exploitable large-scale projects have already been constructed, reveals a wide range, depending on the local resource and cost structure, and ranges from a low of USD 0.03 to USD 0.16/kWh. The average cost for European countries ranges from USD 0.04 to USD 0.18/kWh (Figure 6.1).

A brief review of the LCOE range for hydropower in countries with the largest installed capacity of hydropower today is revealing. At the best sites, the LCOE of hydro is very competitive and among the lowest cost generation options available. However, the majority of new developments will be in less optimal sites than existing hydropower schemes, although this is not always the case. The average LCOE of new developments is more likely to fall somewhere in the middle of the estimated LCOE range presented in Figure 6.2.

The incorporation of small hydropower in the analysis for the United States, Canada and Africa can have a big impact on the range of potential costs. Although small hydro can be a competitive solution for remote locations, its LCOE will tend to be higher than an equivalent large-scale project. Similarly, at the lower end of the range, the incorporation of upgrading projects or the development of hydropower schemes at existing dams without a current hydropower scheme can suggest that hydropower costs are very low, when these tend to be relatively limited opportunities to add new capacity.

Figure 6.3 presents the LCOE of 2 155 hydropower projects plotted against their cumulative capacity that were evaluated in the United States. These represent undeveloped sites, existing dams without hydropower

19 See http://publications.europa.eu/code/en/en-370100.htm

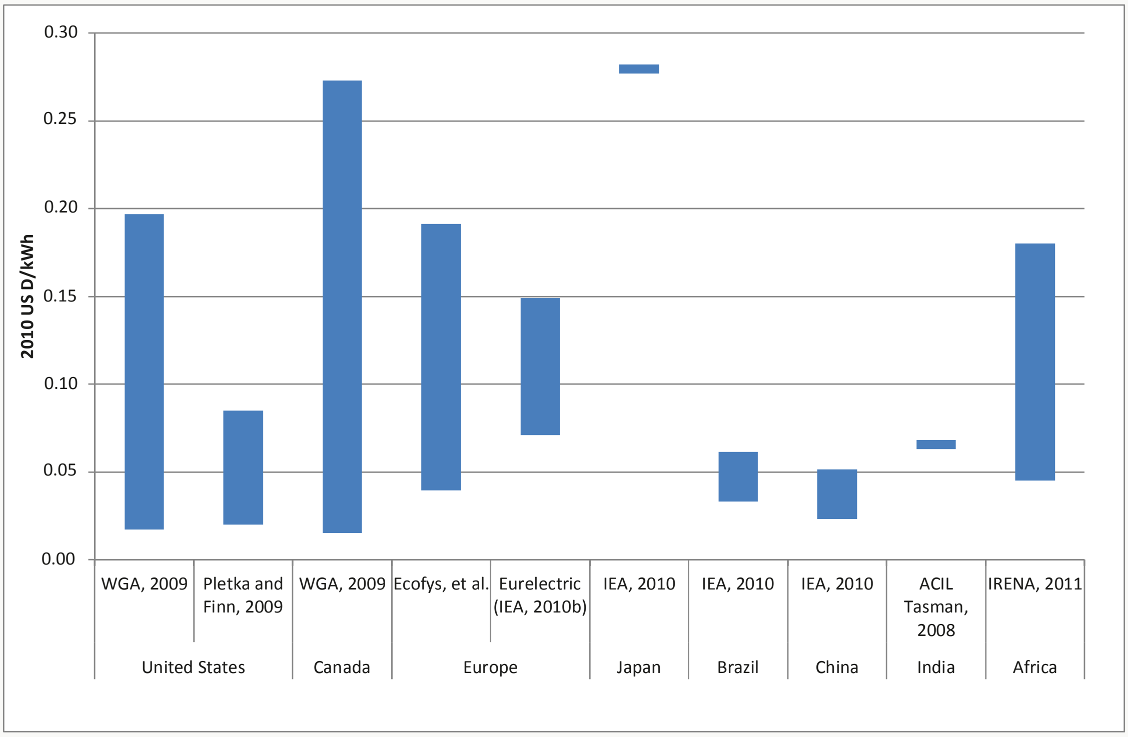

Figure 6.2: Levelised cost of electricity for hydropower plants by country and region
Note: Assumptions on capital costs, capacity factors, O&M costs, lifetimes and discount rates differ. Refer to each study for the details.

Sources: ACIL Tasman, 2008; Ecofys, et al., 2011; IEA, 2010b; IRENA, 2011; Pletka and Finn, 2009; and WGA, 2009.

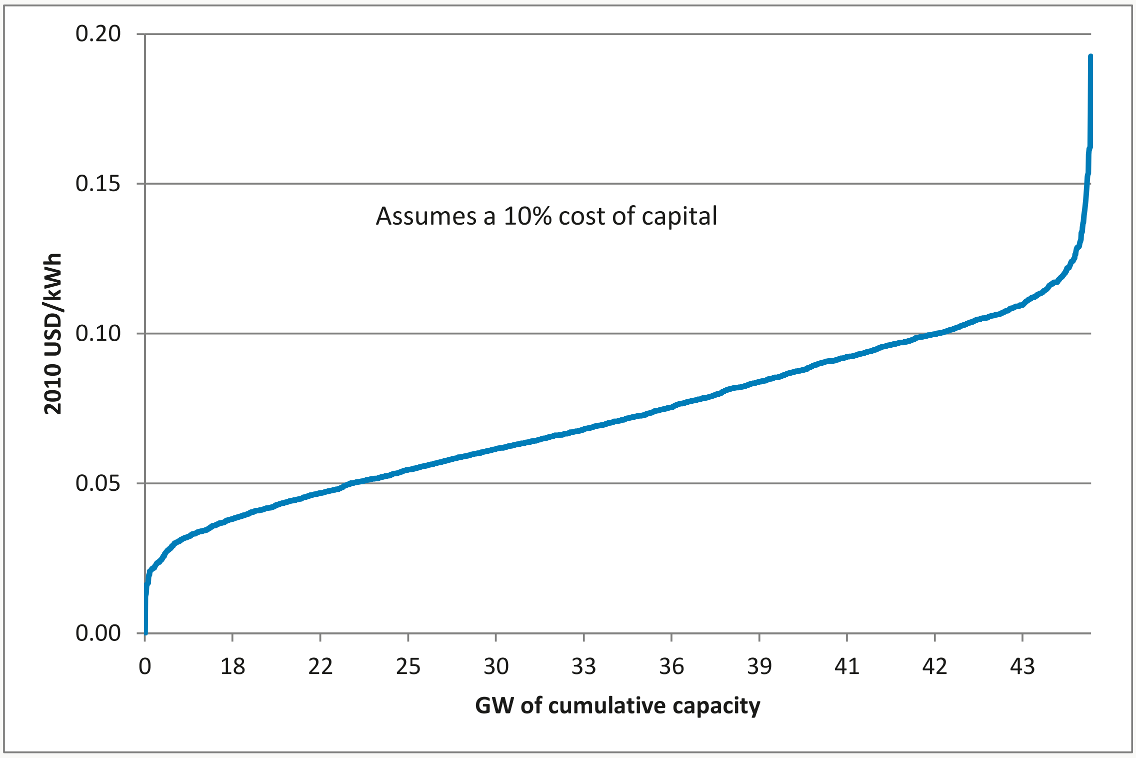

Figure 6.3: The LCOE of hydropower in the United States

Source: Hall, 2003 and IRENA.

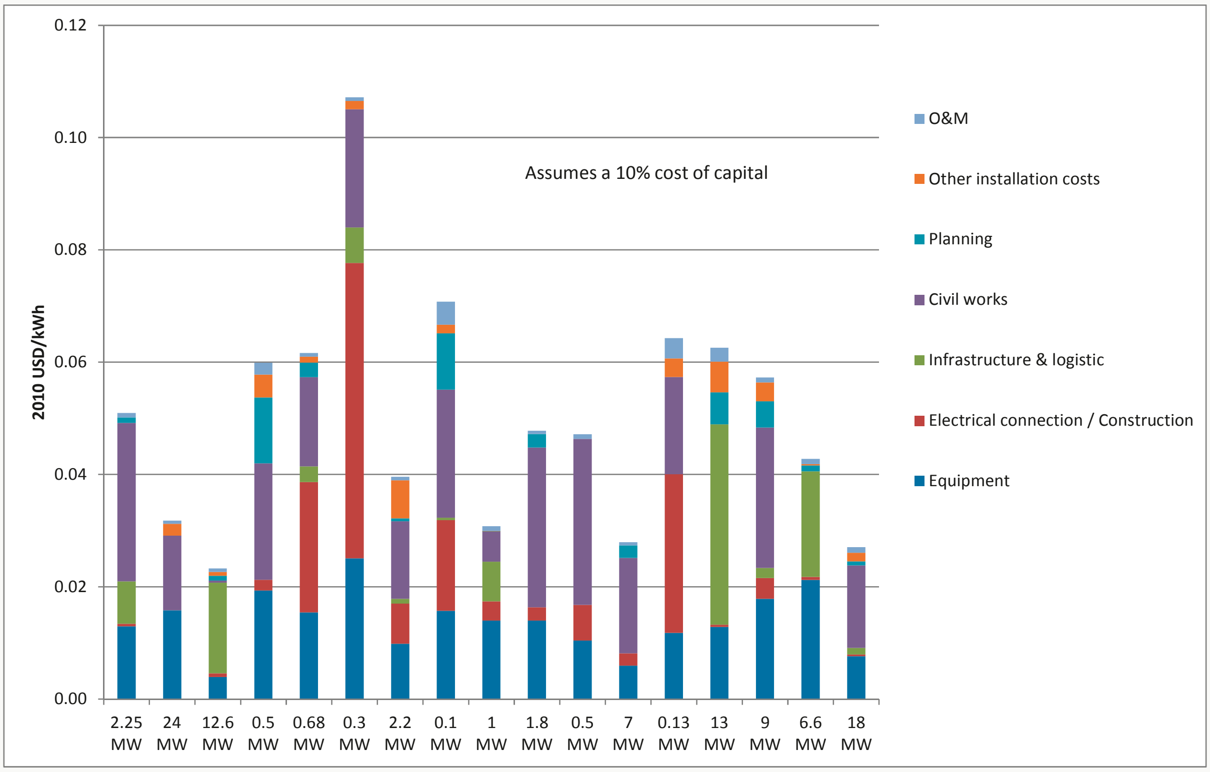

Figure 6.4: The LCOE of small hydropower for a range of projects in developing countries

Source: IRENA/GIZ.

and the expansion of existing hydropower schemes (Hall, 2003). The database includes cost estimates for the capital costs (civil works, electro-mechanical costs, etc.), licensing and mitigation costs to address archaeological, fish and wildlife, recreation or water quality monitoring requirements.[20]

Around 40 % of the capacity studied would come from undeveloped sites, 48 % from existing dams without hydropower schemes and the remainder from expansions at existing hydropower schemes. The average installed cost is USD 1 800/kW with an average capacity factor 52 %. Fixed O&M costs average around USD 10/kW/year while variable O&M costs average USD 0.002/kWh.

The LCOE of the projects evaluated ranged from a low of just USD 0.012/kWh for additional capacity at an existing hydropower project to a high of USD 0.19/kWh for a 1 MW small hydro project with a capacity factor of 30 %. The weighted average cost of all the sites evaluated was USD 0.048/kWh. The LCOE of 80 % of the projects was between USD 0.018 and USD 0.085/kWh.

Figure 6.4 presents the LCOE of small hydropower projects in developing countries, broken down by source. The LCOE of small hydropower projects ranges from a low of USD 0.023/kWh to a high of USD 0.11/kWh. The share of O&M in the LCOE of the hydropower projects examined ranges from 1% to 6 %. The largest share of the LCOE is taken up by the costs for the electro-mechanical equipment and the civil works.

The share of the electro-mechanical equipment in the total LCOE ranged from a low of 17 % to a high of 50 %, with typical values being in the range 21% to 31%. The civil works had the highest contribution to the total LCOE in nine of the projects examined and their share ranged from zero (for an existing dam project) to a high of 63 %. In some remote projects, grid connection and electrical infrastructure dominated while it was significant in a number of projects without being dominant. Similarly, infrastructure and logistical costs can be a significant contributor to overall costs where site access is difficult and/or far from existing infrastructure.

20 The capital and O&M costs were not estimated using detailed, site-specific engineering analysis of the projects, but with capital and O&M tools developed for the project. The actual costs would vary around these estimates.

6.2 HYDROPOWER LCOE SENSITIVITY TO THE DISCOUNT RATE

Given that hydropower is capital-intensive, has low O&M costs and no fuel costs, the LCOE is very sensitive to investment costs and interest rates but less sensitive to lifetime, given the lifetime range typical for hydropower.

The sensitivity of the LCOE of hydropower to different discount rates (3 %, 7 %, 10 %) and lifetimes (40 and 80 years) (IPCC, 2011) is presented in Table 6.1. The LCOE of hydropower projects is not particularly sensitive to assumptions about their economic lifetimes because they are so long. However, because virtually all of the costs are upfront capital costs, the LCOE is very sensitive to the discount rate used. The difference between a 3 % discount rate and a 10 % discount rate is very significant, with the LCOE increasing by between 85 % and 90 % as the discount rate increases from 3 % to 10 %.

Table 6.1: Sensitivity of the LCOE of hydropower projects to discount rates and economic lifetimes

Investment cost (USD/kW)	Discount rate (%)	LCOE (US cents/kWh)	Lifetime (years)	LCOE (US cents/kWh)
1 000	3	1.7	80	1.5
1 000	7	2.5	80	2.4
1 000	10	3.2	80	3.2
2 000	3	3.5	80	2.9
2 000	7	5.1	80	4.8
2 000	10	6.5	80	6.3
3 000	3	5.2	80	4.4
3 000	7	7.6	80	7.3
3 000	10	9.7	80	9.5

Note: base case assumes an economic life of 40 years, a 45 % capacity factor and 2.5 % of capital costs per year for O&M.
Source: IPCC, 2011.

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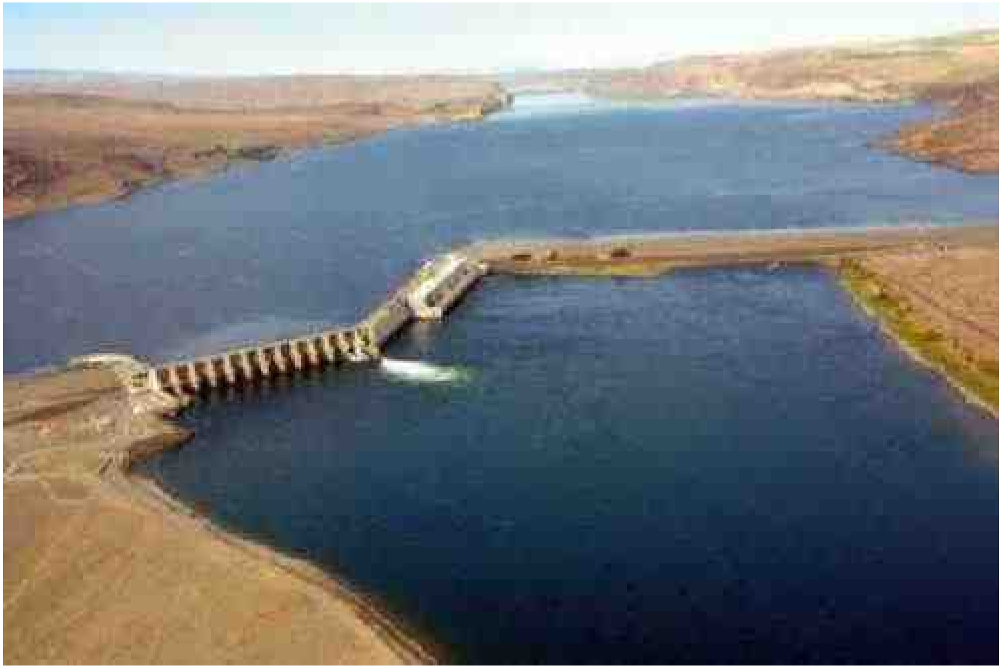

IRENA

International Renewable Energy Agency

IRENA Secretariat
C67 Office Building, Khalidiyah (32nd) Street
P.O. Box 236, Abu Dhabi,
United Arab Emirates
www.irena.org

Attachment 2

Oak Ridge National Laboratory (ORNL) Hydropower Baseline Cost Modeling (ORNL/TM – 2015/14). January 2015. [Executive Summary only]

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OAK RIDGE
NATIONAL LABORATORY

MANAGED BY UT-BATTELLE
FOR THE DEPARTMENT OF ENERGY

ORNL/TM-2015/14

Hydropower Baseline Cost Modeling

January 2015

Prepared by

Patrick W. O'Connor
Qin Fen (Katherine) Zhang
Scott T. DeNeale
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Emma Centurion

UT-BATTELLE

ORNL-27 (4-00)

Executive Summary

Recent resource assessments conducted by the United States Department of Energy have identified significant opportunities for expanding hydropower generation through the addition of power to non-powered dams and on undeveloped stream-reaches. Additional interest exists in the powering of existing water resource infrastructure such as conduits and canals, upgrading and expanding existing hydropower facilities, and the construction new pumped storage hydropower. Understanding the potential future role of these hydropower resources in the nation's energy system requires an assessment of the environmental and techno-economic issues associated with expanding hydropower generation. To facilitate these assessments, this report seeks to fill the current gaps in publically available hydropower cost-estimating tools that can support the national-scale evaluation of hydropower resources.

The report presents the background, framework, methodology, and results of the collection of contemporary cost data and the development of a series of parametric models to predict the initial capital cost (ICC) of hydropower projects. Recent cost data helps provide the economic context for recent hydropower development; the parametric "baseline cost models" are used to generate cost estimates for hydropower projects in various resource categories and are intended to produce generalized, representative estimates suitable for the national or regional-scale evaluation of hydropower economic competitiveness. More sophisticated, bottom-up (as opposed to top-down, parametric) techniques are necessary for the development of individual site costs; however, the parametric approaches described in the report are a necessary simplification to systematically evaluate hydropower potential across the U.S.

Nearly 600 unique cost estimates were gathered from 16 different sources, including reports, market intelligence databases, and private communications with owners, developers and consultants. The scope and extent of each cost estimate varied with many projects lacking data for the costs and risks associated with the licensing, permitting, and development of hydropower projects. Future iterations of this report will tackle the contemporary costs of the licensing and project development processes, but in this initial iteration, references to historical estimates of the cost of licensing hydropower projects are provided within the report.

Based on the United States-only subset of the collected data, the cost of constructing a hydropower plant on existing conduits, on non-powered dams, or along new, undeveloped stream reaches has ranged from \$1000 to \$9000 per kilowatt, with the average canal project averaging \$4100 per kilowatt, the average non-powered dam project costing approximately \$3800 per kilowatt and development along new stream reaches costing approximately \$4900 per kilowatt. In all three cases costs were most noticeably driven by economies of scale (i.e. lower costs) from higher hydraulic head, while only canal projects exhibited meaningful economies of scale from higher installed capacity. Across the timespan of the collected data (roughly 1980 to present), construction costs for hydropower plants have not grown on a real, inflation adjusted basis. On a lifecycle basis, for those plants for which generation estimates were available, the unsubsidized levelized cost of energy (LCOE) of constructing recent hydropower plants has ranged from \$30 to \$180 per megawatt-hour, with the median project

costing approximately $110 per megawatt-hour (excluding licensing) for powering conduits, non-powered dams, and new stream reaches.

In addition to the construction of power generating facilities on previously unpowered infrastructure or stream reaches, costs estimates were also collected for the installation of additional units in existing powerhouses and the rewinding of existing generators; the average addition of a new unit to an existing powerhouse has cost $1930 per kilowatt, and the average generator rewind has cost $114 per kilowatt, but both are subject to strong economies of scale based on the size of the units involved.

Statistical analysis of this cost data has produced a series of cost models that can be used to estimate the cost of constructing a hydropower plant at a reconnaissance level based on key design parameters of capacity (P) and hydraulic head (H). The results of this analysis—the models recommended for use in the evaluation of national-scale hydropower economics—are presented in the table below.

Resource Category	**Cost Model Equation** (ICC in 2012$; P in MW; H in ft)
Non-powered Dams	$ICC = 12{,}038{,}038\ P^{0.980}\ H^{-0.265}$
New Site Development projects	$ICC = 8{,}717{,}830\ P^{0.975}\ H^{-0.120}$
Canal/Conduit projects	$ICC = 11{,}277{,}566\ P^{0.819}\ H^{-0.177}$
Pumped Storage Hydropower projects	$ICC = 2{,}442{,}817\ P^{0.959}$
Unit Addition projects	$ICC = 3{,}030{,}671\ P^{0.811}$
Generator Rewind projects	$ICC = 299{,}461 P^{0.753}$

These modeled costs represent averaged capital costs to construct/modify generating facilities, impoundment structures, and supporting water conveyance infrastructure, and do not necessarily include the additional costs of licensing or environmental mitigation. Substantial discussion is devoted to the classification and evaluation of data quality to provide the reader with a transparent evaluation of the strengths, limitations, and appropriate uses for each of the models. The data quality framework discussed in this document will be used for the continual collection of data and reevaluation of the models, ultimately producing future iterations of the report to document data and methodological improvements, as well as the modeling of additional cost centers, such as operations and maintenance.

Attachment 3

U.S. Department of Energy (USDOE) Modular Pumped Storage Hydropower Feasibility and Economic Analysis. February 13-17, 2017.

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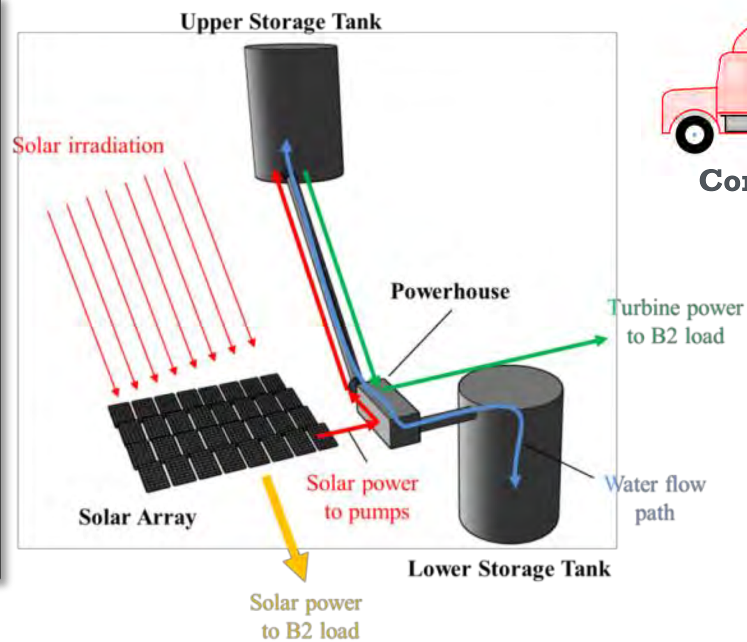
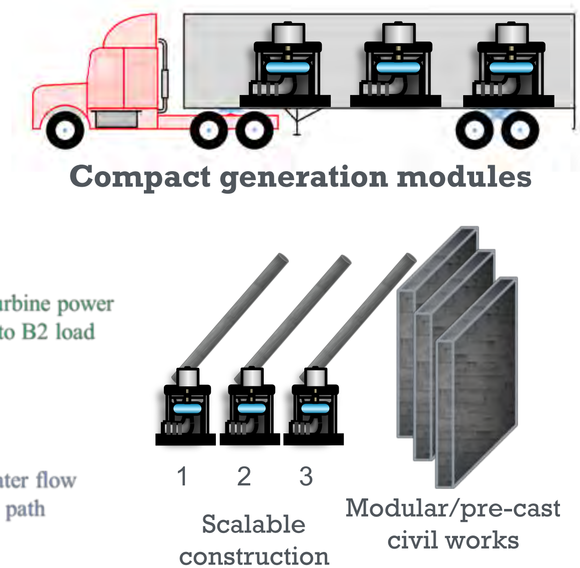
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Conventional Pumped Storage


Ludington Pumped Storage Facility – Photo courtesy of Consumers Energy

Modular Pumped Storage (m-PSH)





Alternative designs

Modular Pumped Storage Hydropower Feasibility and Economic Analysis

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Oak Ridge National Laboratory
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February 13-17, 2017

Project Overview

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Modular Pumped Storage Hydropower Feasibility and Economic Analysis:

- Assess the cost and design dynamics of small modular PSH (m-PSH) development
- Explore whether the benefits of modularization are sufficient to outweigh the economies of scale inherent in utility scale development
- Measure the economic competitiveness of m-PSH against alternative distributed storage technologies (i.e. batteries).

The Challenge:

- Scalability of PSH projects, and whether small modular PSH has competitive advantages over alternative energy storage technologies

Partners: MWH Consulting, Knight Piésold Consulting, Revelo Pumped Storage Company, Biosphere 2, University of Arizona

Next Generation Hydropower (HydroNEXT)

Optimization

- Optimize technical, environmental, and water-use efficiency of existing fleet
- Collect and disseminate data on new and existing assets
- Facilitate interagency collaboration to increase regulatory process efficiency
- Identify revenue streams for ancillary services

Growth

- Lower costs of hydropower components and civil works
- Increase power train efficiency for low-head, variable flow applications
- Facilitate mechanisms for testing and advancing new hydropower systems and components
- **Reduce costs and deployment timelines of new PSH plants**
- Prepare the incoming hydropower workforce

Sustainability

- Design new hydropower systems that minimize or avoid environmental impacts
- Support development of new fish passage technologies and approaches
- Develop technologies, tools, and strategies to evaluate and address environmental impacts
- Increase resilience to climate change

Next Generation Hydropower (HydroNEXT)

Growth

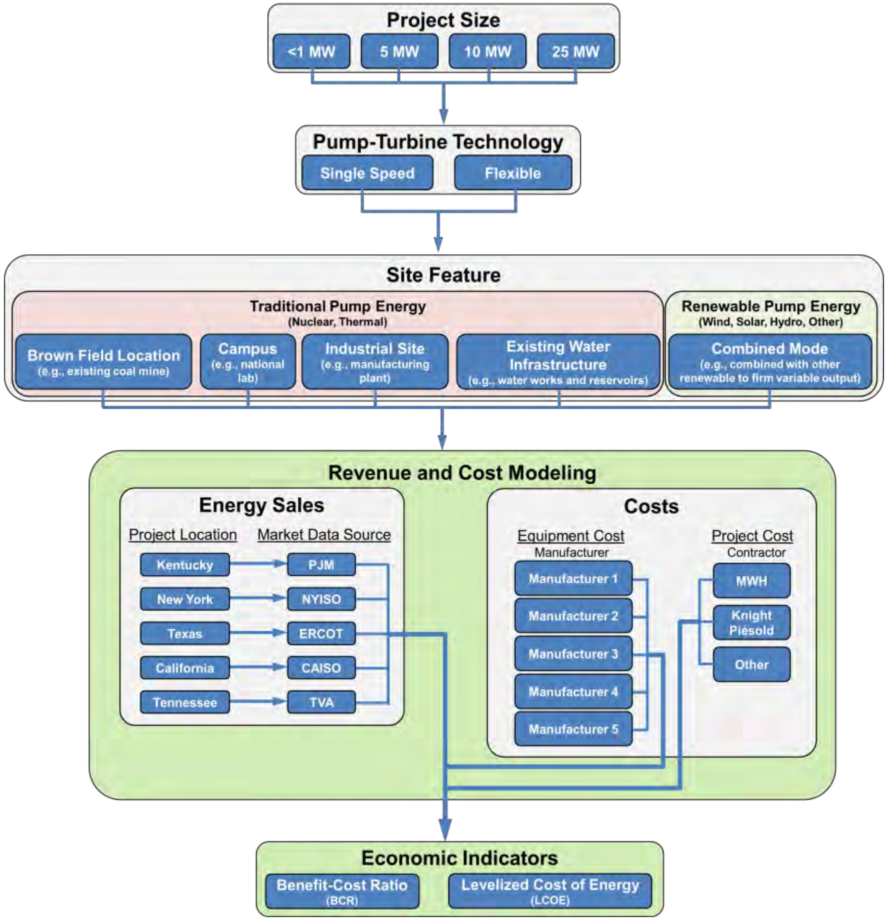
- Lower costs of hydropower components and civil works
- Increase power train efficiency for low-head, variable flow applications
- Facilitate mechanisms for testing and advancing new hydropower systems and components
- **Reduce costs and deployment timelines of new PSH plants**
- Prepare the incoming hydropower workforce

The Impact

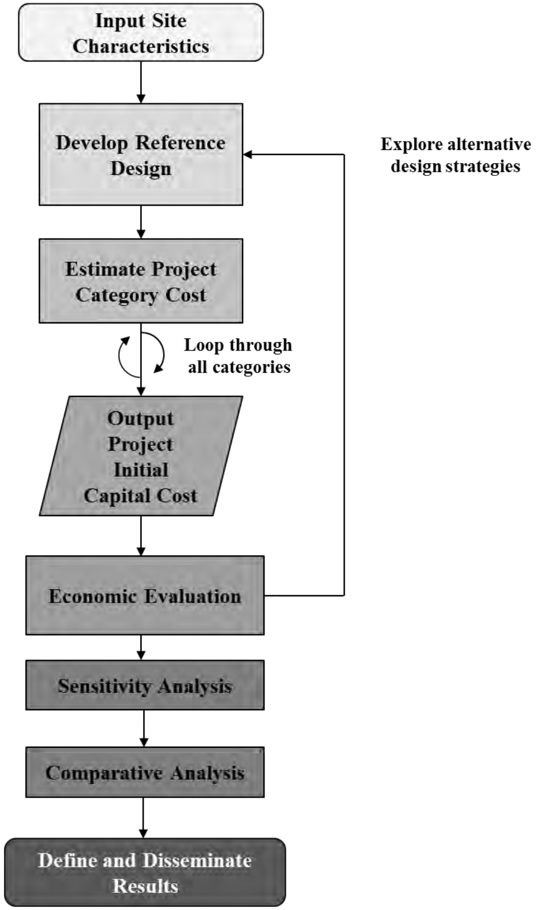
- Small, modular pumped storage hydropower (PSH) systems could present a significant avenue to cost-competitiveness through direct cost reductions, and by avoiding many of the major barriers facing large conventional designs
- Initial Construction Cost (ICC) target of ~$2,000/kW - $3,000/KW
- Cost estimates, design options, potential revenue streams, and feasibility indicators provide industry with an idea of m-PSH viability

The m-PSH project consists of two technical approaches:

1. Targeted case studies



2. Cost modeling tool

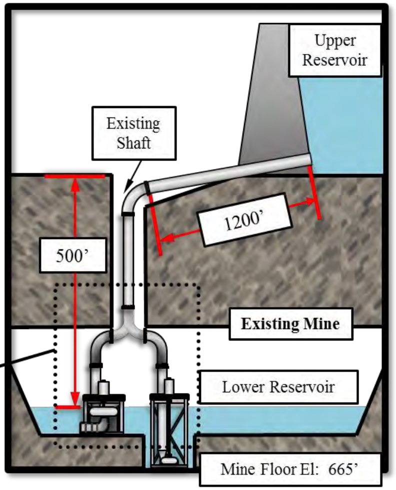


Technical Approach: Case Studies

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

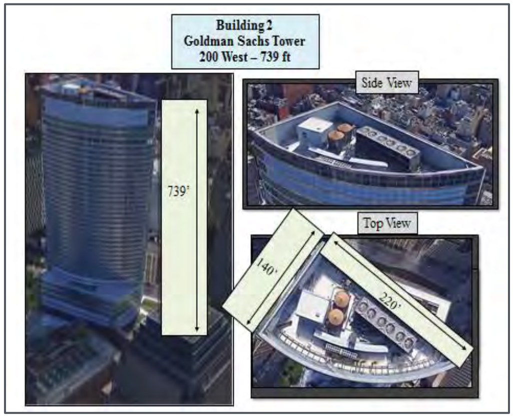
Coal Mine (5MW)

- ICC: $1,700–$2,400/kW (10 hours of storage)
- Closed-loop
- Existing infrastructure
- PJM RTO market
- Regulatory uncertainty and poor regional economic indicators



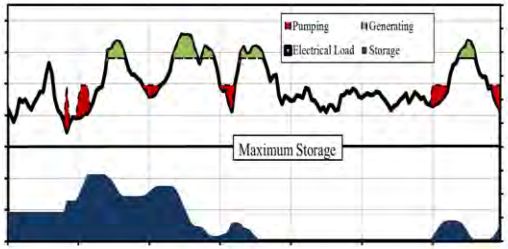
Buildings (305kW)

- ICC: >$3,500/kW (<1 hour of storage)
- Low energy density
- Prohibitive storage tank volume required
- Unrealistic cost-benefit
- Limited market prospects



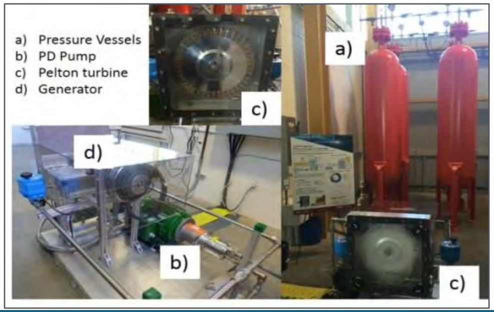
ORNL Campus (5MW)

- ICC: $4,100–$4,700/kW (10 hours of storage)
- Open loop
- No existing infrastructure
- Integrated TVA market
- High costs and low market revenue potential



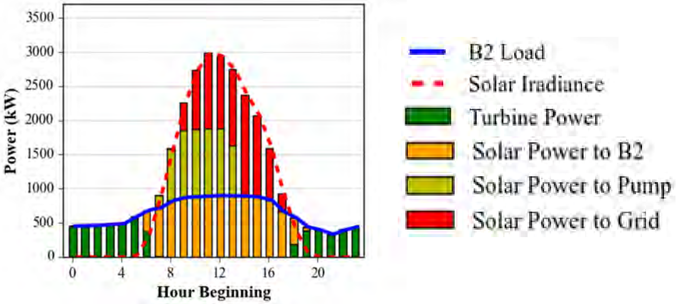
GLIDES (1 kW)

- ICC: >$18,000/kW (10 hours of storage)
- Compressed air/PSH hybrid
- 1 kW prototype at ORNL
- Pressure vessels are major cost driver of economic infeasibility



Biosphere 2 Hybrid (463 kW)

- ICC: $13,600/kW (~13 hours of storage)
- Investigate 'solar powered' m-PSH – store solar for off-peak consumption
- Costs of storage tanks are major driver of economic infeasibility



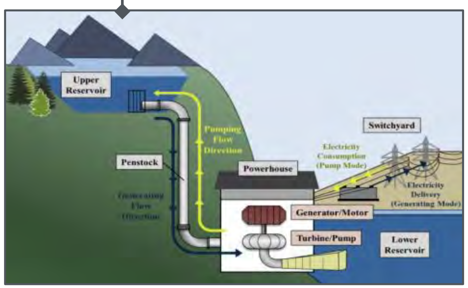
Technical Approach: Cost Model

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Input Site Characteristics

Design head	Status (new, existing, .)
Storage volume	Turbine type
Storage time	Intake type
Reservoir depth	Transmission status
Penstock material	Mitigation requirements

Develop Reference Design → **Develop Project Category Costs** → **Output Total Project Costs**



1. Earth and Civil Works

Upper Reservoir, Lower Reservoir, Conveyances, Powerhouse, Site Access, …

2. Electro-Mechanical Equipment

Major Equipment, Ancillary Plant Electrical, Ancillary Plant Mechanical, …

3. Electrical Infrastructure

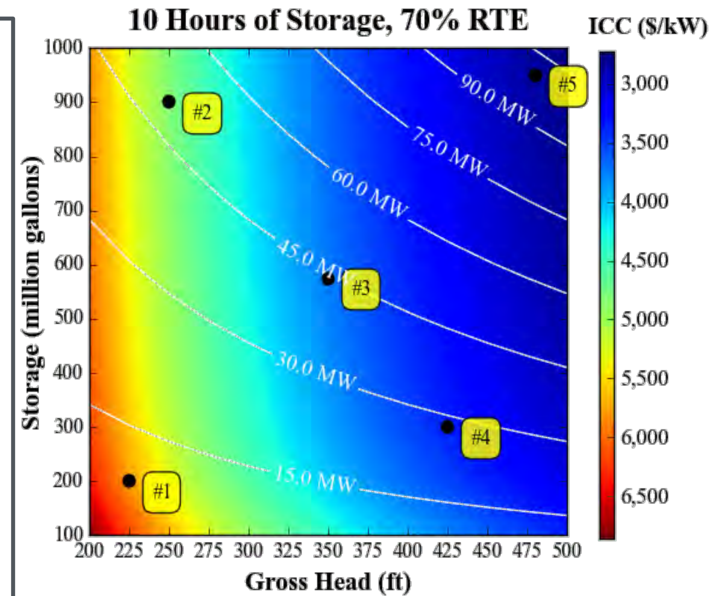
Transmission Lines, Transformers, Switchyard, Substation, …

4. Environmental Mitigation and Compliance

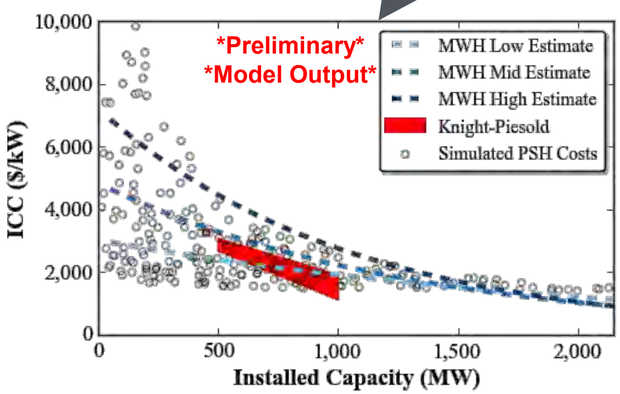
Fish and Wildlife Mitigation, Water Quality Monitoring and Mitigation, Recreation Facilities, Aesthetics, Historical Preservation, …

5. Project Soft Costs

Engineering Construction Management, Owner's Costs, Licensing, …



Cost model estimates at installed capacities between 15 MW and 100 MW



At small installed capacities, cost distributions can be analyzed at several 'test points':

- ➢ Storage costs are proportionately more expensive as head is reduced
- ➢ Conventional approach is prohibitively expensive at installed capacities < 100MW – ***innovation is needed***

Accomplishments and Progress

Technical Accomplishments:

- Site visit of decommissioned coal mine and evaluation for m-PSH potential (2014)
- Case study of m-PSH at ORNL completed for campus sustainability initiative (2015)
- Technical Paper of the Year (2nd Place) at HydroVision International (FY 2015)
- Technical memorandum on cost scaling of GLIDES delivered to DOE (2015)
- Site visit of Biosphere 2 and evaluation of m-PSH and solar potential (2016)
- Catalog of m-PSH equipment and construction costs developed (2016)
- Cost estimating tool complete and available for widespread use (2016).

Publications:

- Technical paper on economic viability of two case studies presented at HydroVision International (FY 2015)
- Technical report on economic viability of three case studies delivered to DOE (ORNL/TM-2015/559, FY 2015)
- Technical paper on m-PSH cost model tool development presented at HydroVision International (FY 2016)
- Technical report on solar/m-PSH hybrid case study delivered to DOE (ORNL/TM-2016/591, FY 2016)
- Technical report on cost model tool and results delivered to DOE (ORNL/TM-2016/590, FY 2016)

Project Plan & Schedule

- Project started October 2014 and ended September 2016.
- All milestones and deliverables were completed on time and within budget.
- Key deliverables were (1) a set of detailed case studies assessing the preliminary feasibility of m-PSH projects and (2) a comprehensive cost estimating tool for closed loop m-PSH projects.

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$750K	$0K	$400K	$0K	$200K	$0K

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators:

- Oak Ridge National Laboratory: Dr. Boualem Hadjerioua, Dr. Adam Witt, Dol Raj Chalise, Rebecca Brink, Miles Mobley, Dr. Ayyoub Mehdizadeh Momen, Dr. Omar Abdelaziz, Dr. Kyle Glueskamp, Adewale Odukomaiya, Ahmad Abu-Heiba
- MWH Consulting: Michael Manwaring
- Knight Piésold Consulting: Norm Bishop Jr.
- Revelo Pumped Storage Company: John Matney
- Biosphere 2: John Adams
- University of Arizona: Dr. Kevin Lansey, Chris Horstman

Communications and Technology Transfer:

- Presentation at HydroVision Conference in Environmental/Social Track (2015)
- Poster presentation at HydroVision Conference (2016)
- Disseminate all technical documents at http://hydropower.ornl.gov/

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY17 / Current Research: Project ended in 2016

Proposed Future Research

- Quantification of the m-PSH type resources present in the US
- Improvements in the cost of storage, either through cost reductions in the civil works associated with storage construction or through strategic siting
- Innovative technical R&D on new designs and manufacturing strategies for modular reversible pump-turbines, and alternative construction strategies and materials
- New models and simulations to better understand how m-PSH can be strategically used as an energy storage technology
- Explore economic feasibility of m-PSH projects that enable greater penetration of intermittent renewables

Attachment 4

Medina, H. and Eldredge, T. 2021. Hybrid Renewable Modular Closed-Loop Scalable PSH System.

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Hybrid Renewable Modular Closed-Loop Scalable PSH System

Authors and inventors: Hector Medina, PhD and Thomas Eldredge, PhD

Technology brief

Our patent-pending[1] technology focuses on a concept described as "hybrid, modular, closed-loop, scalable pumped storage hydro (h-mcs-PSH) and renewable" system with an approximate power capacity range of 0.1 to 10 MW (although larger capacities can be attained). A depiction of the said concept is shown in Fig. 1. The *hybrid* aspect of this technology refers to the incorporation of renewable energy generation, which serves the purpose of increasing the effective energy efficiency of the system and adding extra energy to the grid. The use of solar panels is preferred in some cases since it could add an extra benefit of UV protection to the polymeric reservoirs. The *modularity* allows for fast fabrication and assembly of the system. The *closed-loop* aspect is meant to decrease the level of invasiveness into the environment and facilitate deployment in locations with no existing bodies of water; it also provides a means to conserve water resources. The polymeric reservoirs are typically closed, which essentially eliminates evaporative losses. The *scalability* attribute allows the installed capacity to be varied based on the application or need. The h-mcs-PSH system was devised with an emphasis on reducing equipment and civil works costs, while expediting the timeline for project commissioning. Original funding was made possible through the United States' Department of Energy[2]. Currently our concept is under detailed study. More specifically, small-scale testing, robust computational simulations, and detailed cost analysis are being conducted. A pilot-scale (100kW) is being pursued in collaboration with partners in the southwest region of the Commonwealth of Virginia, U.S., with the goal of implementation in the next two years, if possible. Ultimately, our team

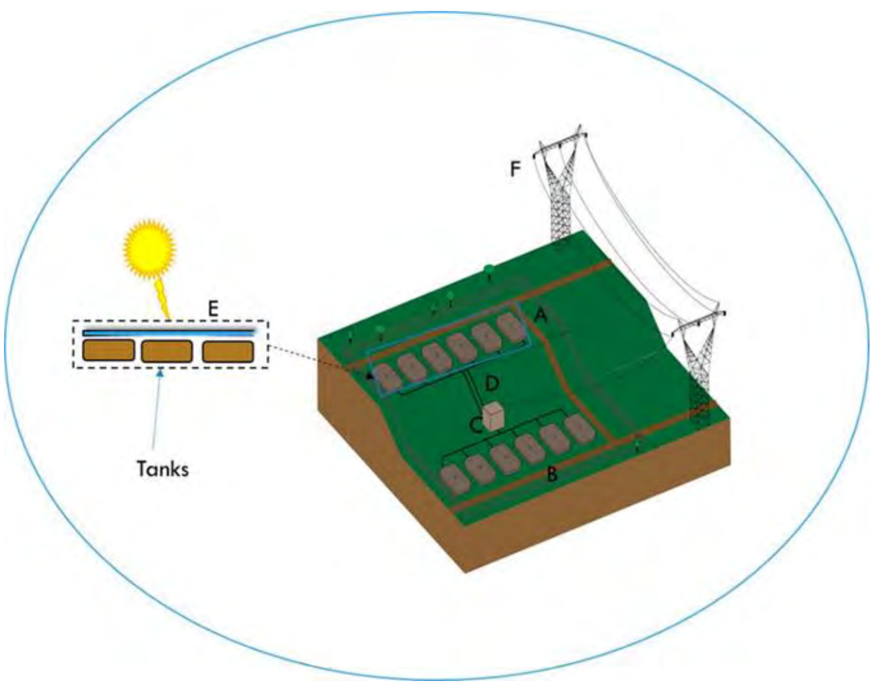

Figure 1: Schematic of the patent-pending hybrid modular closed-loop scalable pumped storage system with the component designations as follows: (A) Upper reservoir; (B) Lower reservoir; (C) Powerhouse (well pump); (D) Penstock; (E) Solar panels; (F) Transmission lines

[1] US 63/146,480

[2] Department of Energy, "Energy Department Announces the Grand Prize Winners of the FAST Prize Competition", October 8 2019. www.energy.gov. Last visited on March, 10, 2021.

expects to bring this technology to full maturity and commercialization. The leading team has had experience contributing to other PSH technologies[3,4].

Challenges, barriers and emerging opportunities

The h-mcs-PSH concept is not intended for very large capacities (more than 20MW), therefore it will not be attractive for single large traditional PSH projects. However, the range capacity can be attractive to industrial, academic campuses, and community projects. The main barriers for implementation could be associated with overcoming the mindset of traditional PSH and accepting novel and disruptive technologies such as the h-mcs-PSH. The opportunities for the use of the h-mcs-PSH system are based on its primary benefits, which include the following:

- Easily deployable in many terrains and locations.
- Very minimal civil works.
- Polymeric tanks can be extremely low maintenance, yet durable, reliable, and long life.
- Closed loop system, which reduces environment invasion and conserves water resources.
- Low cost ($/kW) and estimated 20^+ years of life.
- High efficiency vertical-shaft pump-turbine system, which does not require sub-terrain pump-turbine building.
- Solar or other various renewable energy resources can be incorporated.
- Potential for expedited or exempted FERC (Federal Energy Regulatory Commission) licensing, as described below.

FERC regulates non-federal hydropower resources in the U.S. It is well known that any activity that results in discharges into waters of the United States cannot be licensed by a federal agency unless a CWA (Clean Water Act) Section 401 certification is issued. Therefore, FERC licensing of hydro-power projects is subject to CWA Section 401 certification. Because the h-mcs-PSH system is closed loop, and therefore has no discharge into natural bodies of water, it is the authors' opinion that the CWA Section 401 certification will likely be waived in most circumstances, which should greatly expedite any required FERC licensing.

FERC issues three types of authorizations to proceed with hydropower project development and construction. They offer licenses, which if granted, can take up to five years to obtain. Secondly, FERC offers two types of licensing exemptions, a conduit exemption and an exemption for projects of 10-megawatt (MW) or less, which meet certain requirements. The authors believe the latter will likely apply for the proposed h-mcs-PSH system, particularly for system capacities of 10 MW and lower.

Cost-efficacy and feasibility

There was not much construction of new PSH projects in the U.S. in the last 25 years due largely to high civil costs, licensing hurdles, and long project time lines[5]. The Electric Power Research Institute estimates the installed capital cost for pumped-storage hydropower varies between near $2,000 and $5,100/kW, as compared to $2,500/kW to 3,900/kW for lithium-ion batteries[6]. However, lithium-ion batteries have a life ranging from 1000 to 10000 cycles. Based on two cycles per day, lithium-ion batteries have a life ranging from 1.4 to 13.7 years. The h-mcs-PSH system has an estimated life of at least 20^+ years. Experimental and computational analyses are underway for determining a refined estimate of the expected life. The cost of the proposed h-mcs-PSH system is approximately equivalent, and in some cases lower than lithium-ion

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[3] Hadjerioua B, Eldredge T, Medina H, DeNeale S. Hydrodynamic and Structural Response Modeling of a Prototype Floating Membrane Reservoir System for Pumped Storage Hydropower. Journal of Hydraulic Engineering. 2019 Jul 13;145(9):04019032.
[4] Hadjerioua, Boualem, Eldredge, Thomas, Medina, Hector, and Deneale, Scott T. "Design and Modeling of a Prototype Floating Membrane Reservoir System Application for Pumped Storage Hydropower". ASCE EWRI Congress, Pittsburgh, PA, May 2019.
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batteries, and the life of h-mcs-PSH is approximately two to three times longer. This results in the h-mcs-PSH system being more cost effective and marketable than lithium-ion batteries.

In addition, on average, in order for conventional PSH projects to end up costing below $3,000/kW, the installed capacity must exceed 600 MW. Based on estimated cost analysis, the h-mcs-PSH is more economically attractive than the average conventional PSH project on a $/kW basis. Furthermore, when the renewable component is included, although the capital cost slightly increases, the overall benefit is enhanced due to the extra energy generated, which can be invested in the system itself or provided to the grid. See Fig. 2.

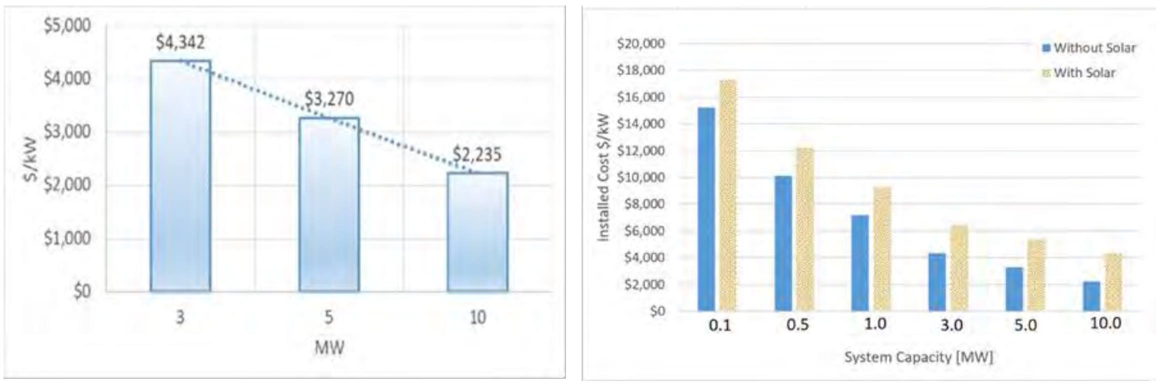

Figure 2: (Left): Estimated capital costs for h-mcs-PSH systems per kW installed for 3, 5 and 10 MW systems, not including renewable component. (Right): Estimated installed system costs with and without solar panels, for system capacities ranging between 100 kW to 10 MW. The cost of the solar panels was based on generation occurring during periods of sunshine at the system capacity (MW).

Potential beneficiaries & use cases

The h-mcs-PSH system is modular and scalable for sizes in the range of 0.1 to 10 MW, and it does not rely on natural bodies of water being present. The h-mcs-PSH system can be attractive to industries that require relatively large amounts of electricity, including the manufacture of aluminum, steel, plastics, and paper. Often these industries generate a portion of their own electricity. Using h-mcs-PSH, industries can optimize their electricity consumption and provide demand response. In addition, this technology is highly suitable for small island grid systems and for isolated and remote systems around the world.

Another very attractive aspect of the h-mcs-PSH system is the incorporation of renewable resources. For the foreseeable future energy demands are largely expected to be met by renewable resources to limit greenhouse gas emissions. One desirable feature of high energy density fossil fuels is the ability to store and transport them, and this capability is often lacking with renewable resources. However the h-mcs-PSH system offers the ability to store energy generated from renewable resources (i.e. solar and wind), which offers the possibility of replacing more fossil fuels with renewable energy.