Introduction:

In January, 2016, the United Nations put forth **17 Sustainable Development Goals** (also known as **Global Goals**) to help countries develop sustainable practices while working to improve the quality of life for its citizens. One such goal, **Sustainable Development Goal #7: Affordable and Clean Energy**; focuses on developing ways to power our world equitably, and sustainably. The lesson plan below focuses on two sub-goals or indicators of this goal:

- By 2030 increase substantially the share of renewable energy in the global energy mix
- By 2030 double the global rate of improvement in energy efficiency

The activities included use an inquiry approach to introduce the concept of sustainable development and energy practices, specifically with regard to wind power, a renewable energy resource. These activities challenge the students to explore the effects of turbine blade number and shape, windmill orientation, and gear/pulley ratio on the effectiveness of energy production in a variety of wind conditions. Ultimately, students will work to design a windmill that maximizes energy production during a 1 minute recording period. In doing so, students explore the two sub-goals listed above. If students can create a more efficient design, perhaps more countries will invest in this renewable energy resource.

Background Information:

Approximately 97.4 quadrillion British Thermal Units (BTU's) (or 1.03×10^{20} J) of energy are used in the United States each year to produce electricity. The primary energy sources to generate this electricity in the country are petroleum, natural gas, coal, renewable sources, and nuclear power. Of these sources, renewable resources collectively account for only 12-15% (~~combined~~) of production.

One of these renewable energy alternatives is wind power. Wind is created from the uneven heating of the air at the earth's surface. Land and water formations vary in the angle at which the sun's rays (heat source) hit, leading to this variability in heating the air near the Earth's surface. Due to increased movement of molecules, warm air is less dense than colder air, causing the warm air to rise. As the air moves away from the surface, it cools, slowing the movement of the molecules that comprise air and making it denser. Thus, the cold air moves toward the surface as the heated air rises (air movement). This air movement contains kinetic energy which can be harnessed and converted into electricity.

Currently, wind power accounts for approximately 5.6% of energy production in the United States. Harnessing the wind is not a new idea. Windmills date back to 900 AD. The use of wind turbines for the generation of electricity in rural areas in the United States occurred during the early 1900's, and became more widely used in areas such as California in the 1980's. Currently, the United States ranks 2nd behind China in the global wind market according to https://gwec.net/globalfigures/graphs, with Texas ranked as the highest producer in the United States (although the state's ranking falls when compared to the total amount of energy production in the state). Illinois ranks around 5th in wind energy production in the U.S., according to https://www.eis.gov/todayinenergy/detail.php?=15851.

Wind turbines convert kinetic energy into electrical energy. Wind turns the turbine's blades, which then spin a shaft. This shaft is connected to a generator that makes electricity via induction. Several turbines, such as on a wind farm, can be hooked together to feed their power to a transformer and then to transmission lines.

The basic parts of a large-scale wind turbine include the blade, hub, nacelle, and tower. The hub is on the front of the turbine, where the blades attach, and what they spin around. Inside the hub there may also be some gears and a shaft. Specifically, the nacelle contains a shaft, gearbox, and generator. There may also be an anemometer which is used to measure wind speed attached to the nacelle. The tower is the structure that holds the turbine up. When measuring turbine height, the measurement goes from the center of the hub to the ground.

Creating a turbine that achieves maximum efficiency in the real world requires considering multiple variables. The air foil design of the blades is important for lift. The blades operate on the same principle as an airplane wing in which greater lift and less drag are desirable. Another consideration is the cross-sectional area of the wind swept by the blades. That will depend on the overall length of the blades less the hub region. The number of blades included in the design will also impact performance. The number of blades in a commercial windmill, however, is an optimization of cost, safety, aesthetics, and noise in addition to performance. The angle the blades make with the plane of the hub is also a consideration. Since the optimal value can change with wind speed and turbine rpm, sophisticated turbines are able to alter their blade angle (pitch), sometimes selecting a suboptimal value for safety, longevity, or the performance of other components.

Since large-scale turbines rotate rather slowly by design, simple conversion to electrical energy would be minute. The addition of a gear system to the turbine shaft greatly increases the voltage output from the generator. In a simple design, there may be two gears connecting the movement and speed of the turbine blades to the shaft that drives the generator. A difference in gear diameters (or equivalently the number of teeth on the perimeters) creates a gear ratio that impacts the relative speed of the two shafts. If the gear connected to the hub is significantly larger in diameter than the one it is meshed with on the shaft for the generator, the generator shaft must rotate faster in the proportion of that gear ratio.

Logistics:

Next Generation Science Standards:

- HS-PS3-3: Design, build and refine a device that works within given constraints to convert one form of energy into another form of energy.
- HS-PS3-2: Develop and use models that illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motions of particles (objects) and energy associated with the relative positions of particles (objects).
- HS-ETS1-1: Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.
- HS-ETS1-2: Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

Objectives:

- Students will use wind to convert mechanical energy to electrical energy.
- Students will design, develop, test, and refine prototypes of turbine blades.
- Students will explore the relationship between gear/pulley ratio and turbine orientation to wind and generated power.
- Students will maximize energy production during a one minute sustained recording.
- Collect, organize, and analyze data

Materials:

(per groups of 2-3 students)

- Fan
- Scissors
- Manila Folders
- 12 Dowel Rods
- 1 Hub
- Stand, pulley set up (2 pulley with belt)
- Alligator clips
- LabQuest , voltage probes, and resistor

(per class)

- 2-6 Industrial Fans

Items can be altered, depending on budget. One fan can be shared as a class, and set in a "testing area". Industrial fans can often be borrowed from the school's janitorial department.

While a large portion of our wind turbine set up is home-made, commercially made wind turbine units can be purchased from a variety of sources. Often, these materials can be adjusted to suit the requirements of the lesson. A few sources are listed below.

- https://www.homesciencetools.com/product/wind-turbine-science-kit/?gclid=EAIaIQobChMI4LTm9vLI2QIVVVmGCh3bqAopEAQYASABEgIBF_D_BwE

- http://www.eaieducation.com/Product/351489/KidWind_Wind_Turbine_Hub_-_3_Pack.aspx?utm_source=Amazon&utm_medium=Amazon&utm_campaign=Amazon&gclid=EAIaIQobChMI4LTm9vLI2QIVVVmGCh3bqAopEAQYAiABEgJgRvD_BwE

- https://www.carolina.com/catalog/detail.jsp?prodId=183251&s_cid=ppc_gl_products&utm_source=google&utm_medium=cpc&scid=scplp183251&sc_intid=183251&gclid=EAIaIQobChMI4LTm9vLI2QIVVVmGCh3bqAopEAQYBCABEgJisPD_BwE

- http://www.studica.com/us/en/kidwind-project/basic-turbine-building-parts/kw-btpart.html?ex_ref=google_feed&gclid=EAIaIQobChMI4LTm9vLI2QIVVVmGCh3bqAopEAQYDCABEgIkWPD_BwE

If a LabQuest set up is not available for recording measurements, voltmeters or multimeters (found in a variety of hardware shops) are a viable option.

Advanced Preparation:

For Challenge 1: decide ahead of time where the fans and stands will be positioned in the room. These should be placed at individual tables, where three groups of students will work (one windmill per group but one fan per 3 groups of students).

For Challenge 2: Place the industrial fans at right angles to each other within the classroom. These fans will cycle on and off at a rate of 30 seconds from each direction. In front of these fans, place a long table, upon which the groups will place their turbines for testing.

Suggested Approach:

Challenge 1:

Begin the lesson by surveying the students for prior knowledge on where electricity comes from, what energy sources are available, and which are renewable or non-renewable sources. Further review and discuss what it means for a source to be renewable. Allow ample time for students to share and clarify their ideas. Ask the students to discuss some of the benefits and costs of each of these energy sources; specifically when it comes to the renewable sources.

Inform the students of the **United Nations (U.N.) Sustainable Development Goals**; specifically, **Sustainable Development Goal #7: Affordable and Clean Energy**, which focuses on developing ways to power our world equitably, and sustainably. Explain that the students will be working on two parts of this goal:

- By 2030 increase substantially the share of renewable energy in the global energy mix
- By 2030 double the global rate of improvement in energy efficiency

One way of achieving the goal of increasing availability or use of renewable energy into the global energy mix is to focus on creating turbines that can obtain this energy at maximum efficiency.

Explain that they will be working in pairs or groups of 3 to design a wind turbine that works at the maximum possible efficiency (greatest fraction of power transferred from wind). First, they will work on the efficiency with regard to the turbine blades.

Place the students into their groupings and distribute to each group the following materials: one stand, a generator and hub, pulley system, 12 dowel rods (for the blade vanes), alligator clips, manila folders, scissors, tape, a load resistor, voltage probes and a LabQuest.

Demonstrate how to place the dowel rod/ blades in the hubs, how to set up the turbine stand with the generator, as well as how to attach the alligator clips and the LabQuest for measurement (and how to use this devise to measure energy output):

- For the first round of the challenge, students create the turbine blades out of manila folders and place on the blade vanes (dowel rods).
- These blades are then fitted into the hub and the hub placed on the stand, and attached to the generator.
- Students are allowed to fasten the windmill to the stand to prevent rotation.
- At each set up, or table, there is one fan. This fan is used to create the wind energy.

Explain that three groups will test at one table. The groups can test repeatedly, recording and saving their energy output with the LabQuest setup (a voltage or multimeter can also be used to obtain a voltage reading if no LabQuest equipment is available). The students can also redesign and retest until the allotted time expires.

As the students work and test their designs, rotate around the classroom, facilitating discussion about the design and orientation of their blades. Allow this round to continue for 25 minutes.

Debrief Challenge 1:

Reconvene the students into a large group and have the students describe what worked well and what did not with their blade designs. Ask the students to consider any scientific principles that might account for their findings.

Momentum Transfer – Much like a kite, the basic operation of the turbine blades is deflecting air. Blade angles matter. If they are too shallow, the wind is trying to knock the tower down. If they are too steep, not much air encounters the blades.

Bernoulli's Principle – Momentum transfer can be augmented with lift. Doming the blade on the side it is turning toward will increase the pressure differential between the front and back faces of the blade. This could be technically difficult to achieve on a small model such as ours.

Rotational Inertia – This is probably a modest factor in our artificial, controlled environment of sustained high wind. In the real world, high rotational inertia turbines (many long blades) might have trouble getting started in low wind but would sustain motion between intermittent gusts (much like the flywheel in old single-cylinder tractors.)

Newton's Third Law (action-reaction) – People consider what the air is doing to the blades but often overlook what the blades are doing to the air. While making the density of blades great seems like the way to maximize propulsion, if deflected air from the back of one blade hits the front face of the next, that is counterproductive. The same goes for Bernoulli's Principle. The low pressure on the lead face of one blade can't also be in the vicinity of the trailing face of the adjacent blade or the effect is negated. (WWI biplanes separated and offset the wings considerably.) Air flow must also remain laminar. Turbulence will degrade the performance of everything.

Conservation of Energy – Any noise, wobble, or otherwise unnecessary motion represents some portion of the total energy that is not becoming electrical energy, thus lowering efficiency.

Friction – Although it is required for our pulley system to work in the second challenge, any other rubbing among moving parts represents undesired losses due to work by friction.

Ask the students how much energy (or what percentage) they think they should obtain from their apparatus; require explanation of their answers. You can include the theoretical limit on percentage of energy extracted, ~60% (Betz's Law.) Ask them (and then discuss) how wind speed is involved, and how they believe this works within the turbine system.

Lastly, identify the two devices from each table that had the highest measurement on average during the recording. These two groups from each table will advance to the next challenge (while the members from the third group will assist the advancing two). ~~Alternatively, declare the winner of the challenge, and move on to the next challenge.~~????

Challenge 2:

Explain to the students that the next challenge includes a wind test that mimics more realistic changes in wind direction. The wind will now be created by two rows of industrial fans placed at right angles to each other within the classroom. These fans will cycle on and off at a rate of 30 seconds from each direction.

Direct student attention to the long table, upon which the groups will place their turbines for official testing. The table is subdivided into 0.5 m wide sections. During testing, all portions of their device and stand must stay within their allotted space, even as it pivots in the wind. Students may not touch their device or stand during official testing.

Ask the students to observe the components of the turbine system, other than the blades. They should notice that there is a pulley system. Explain that most turbines have a gear box, but this design will utilize a pulley system instead.

Inform the students that for this testing, they should now evaluate how the pulley shaft diameters could be manipulated for their benefit. They can build up either or both shafts by wrapping any number of small rubber bands around them,

In addition, students should consider a mechanism to orient their turbine in the wind for maximum performance. Traditionally this is done with a tail.

Ask the students:

- ***What benefit might either of these features add?***

Facilitate discussion as the students work, redesign and test. Again, students should record and save their results for their energy output. Allow this round to continue for 25 minutes.

Debrief Challenge 2:

Reconvene the students once more into a large group. Discuss the successes of each design and ask the students to relate these back to the scientific principles discussed previously or additional ones.

Mechanical Advantage – How pulley shaft diameter ratios affect the relative speeds of the turbine and generator.

Torque – What tail shape gave the most stability for its size.

Identify the best two devices, and discuss their designs. Ask the students to relate their activity to the engineering and design process, and how they worked to optimize their designs.

Next, facilitate a discussion about how these activities relate to the **U.N. Sustainable Development Goal.** In the discussion, it should be clear that the students we working to optimize their design such that the efficiency of energy production was increased. However, the students may not easily relate to how this might lead to more countries adopting this technology.

At this point, allowing for students to research the cost of current turbine designs, and contemplate what the cost of their design might be in important. Once the students have researched these costs, reconvene and lead a discussion on which designs worked best to optimize energy output while maintaining a low cost alternative that would allow more countries to partake in this technology.

You can extend this conversation by considering other factors such as the environmental impact of their designs (which takes up more space, is louder, or threatens wildlife and why this matters).

Resources:

http://www.kidwind.org/
http://www.un.org/sustainabledevelopment/development-agenda/

https://www.eia.gov/tools/faqs/faq.php?id=92&t=4
https://www.eia.gov/tools/faqs/faq.php?id=427&t=3
http://michaelbluejay.com/electricity/cost.html#kilowatt
https://gwec.net/globalfigures/graphs
https://www.eia.gov/todayinenergy/detail/php?=1851