CEE 176B Final Project Report

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Introduction: The purposes of transitioning towns, cities, states, countries, and the world to 100 percent clean, renewable WWS (Wind-Water-Solar) energy and storage for everything and to eliminate non-energy sources of emissions are to eliminate air pollution mortality and morbidity, reduce and then eliminate global warming, and provide energy security. In a 100 percent WWS world, all energy sectors are electrified or powered with direct heat, where the electricity and heat are provided by WWS.

Calculating End-Use Energy Demand: The state of **California** has been chosen for the purpose of this project, given the significance of the state with the nation's largest gross state product.

Fuel	Residential	Industrial	Transportation
Oil	0.2	0.82	0.19 or 0.36
Natural gas	0.2	0.82	0.19 or 0.36
Coal	0.2	0.82	--
Electricity	1	1	1
Heat for sale	0.25	0.25	--
WWS heat	1	1	--
Biofuels/waste	0.2	0.82	0.19

Table 1: Factors to multiply BAU End-Use Energy by to obtain WWS Energy Needed

The total end-use energy in California for 2020 was obtained (see Table 2) in Trillion Btu, and accordingly converted to TWh using the conversion, 1 Trillion Btu = 0.293 TWh. Reduction factors from Table 1 were applied to obtain the total WWS Energy needed. Since renewables already have a fair share in the Californian electricity grid, the additional WWS energy needed comes out to around 828 TWh (Table 3) and is calculated by summing the WWS energy corresponding to coal, natural gas, all fuels, nuclear, biomass and electricity imports.

Category	Energy Consumption (Trillion Btu)	Energy Consumption (TWh)	Reduction Factor	WWS Energy (TWh)
Coal	28	8.204	1	8.204
Natural Gas	2151.1	630.2723	-	-
Residential	668	195.724	0.2	39.1448
Industrial	1458.1	427.2233	0.82	350.323106
Transportation	25	7.325	0.19	1.39175
Motor Gasoline excl. Ethanol	1357.8	397.8354	0.19	75.588726
Distillate Fuel Oil	528	154.704	0.46	71.16384
Jet Fuel	337.7	98.9461	0.46	45.515206
HGL - Hydrocarbon Gas Liquids	58.2	17.0526	0.19	3.239994
Residual Fuel	126.1	36.9473	0.36	13.301028
Other Petroleum	299.6	87.7828	0.82	71.981896
Nuclear Electric Power	169.8	49.7514	1	49.7514
Hydroelectric Power	187.4	54.9082	1	54.9082
Biomass	400.2	117.2586	0.82	96.152052
Other Renewables	657.3	192.5889	1	192.5889
Net Electricity Imports	11	3.223	1	3.223
Net Interstate Flow of Electricity (Exports)	757.5	221.9475	1	221.9475

Table 2: California Energy Consumption Estimates 2020, Source: Energy Information Administration, https://www.eia.gov/state/?sid=CA#tabs-1

Resource Allocation: Once the additional WWS Energy required is calculated, it is proportioned as follows (Table 3): 40% - wind, 40% - utility-scale solar and the rest to rooftop solar. Solar power has been growing rapidly in the U.S. state of California because of high insolation, community support, declining solar costs, and a renewable portfolio standard which requires that 60% of California's electricity come from renewable resources by 2030. Hence, the overall percentage of solar allocated (60%) is higher than wind (40%).
However, rooftop solar is allocated a smaller percentage than utility-scale solar for the following reasons:

- Because of economies of scale, large solar farms are cheaper than rooftop solar.
- Utility-scale solar farms offer a lot more flexibility in terms of where they can be located.

Since most of California's population is located along the coast, a significant portion of the wind resource is allocated offshore (60%) with the rest onshore (40%) to minimize transmission and distribution costs and losses.

Additional WWS Energy Needed (TWh):	828.98
Onshore Wind 16%	132.64
Offshore wind 24%	198.96
Utility-scale Solar 40%	331.59
Rooftop Solar 20%	165.79

Table 3: Resource allocation to Wind and Solar

Calculation of number of devices:

Wind:

Onshore wind requirement = 132.64 TWh/yr / (8760 h/yr) = 15.14 GW
Offshore wind requirement = 198.96 TWh/yr / (8760 h/yr) = 22.71 GW

Wind - onshore:

Average hub height = **100 m**
Annual average wind speed 100 m above surface level = **5 m/s** (taken from NREL Wind Resource Map)
Average nameplate capacity of wind turbine = **3 MW** = 3000 kW
Average blade diameter = 125 m

$C_F = 0.087 \times V_m - P_r/D^2$

$= 0.087 \times 5 - (5000/125^2) = 0.243$

Area of California = 423,971 km^2

Average nameplate capacity of wind farm = 1000 MW
Average power density = 20 MW/km^2
System Efficiency = 0.9
Land required = 15.14 * 10^3 MW / (0.243 * 0.9 * 20 MW/km^2) = 3461.63 km^2
Number of wind farms required = 3461.63 km^2 / (1000 MW / 20 MW/km^2) = 69
Number of wind turbines required = 69 wind farms * 1000 MW/wind farm/3 MW/turbine = **23,078**
Footprint per turbine = 3.14 x 5 x 5 / 4 = 19.63 m^2
Total footprint = 23078 * 19.63 / 10^6 = 0.45 km^2

Percentage of California area consumed = 3461.63 km^2 / 423,971 km^2 = **0.82%**

Wind-offshore:

Average hub height = **100 m**
Annual average wind speed 100 m above surface level = **10 m/s** (taken from NREL Wind Resource Map)
Average nameplate capacity of wind turbine = **10 MW** = 10000 kW
Average blade diameter = 200 m

$C_F = 0.087 \times V_m - P_r/D^2$

$= 0.087 \times 10 – (10000/200^2) = 0.62$
Average nameplate capacity of wind farm = 2000 MW
Average power density = 30 MW/km^2
System Efficiency = 0.9
Land required = 36.124 * 10^3 MW / (0.62 * 0.9 * 30 MW/km^2) = 1356.74 km^2
Number of wind farms required = 1356.74 km^2 / (3000 MW / 30 MW/km^2) = 14
Number of wind turbines required = 14 wind farms * 3000 MW/wind farm/10 MW/turbine = **4070**

Footprint per turbine = 3.14 x 15 x 15 / 4 = 176.71 m^2
Total footprint = 4070 * 176.71 / 10^6 = 0.72 km^2

Percentage of California area consumed = 1356.74 km^2 / 423,971 km^2 = **0.32%**

Solar:

Utility-scale solar:

Utility-scale solar requirement = 331.59 TWh/yr / (8760 h/yr) = 37.85 GW

Average nameplate capacity of solar farm = 300 MW
Average capacity factor = **0.33**
Power density = 36 MW/km^2
System efficiency = 0.9
Land required = 37.85 * 10^3 MW / (0.33 * 0.9 * 36 MW/km^2) = 3540.31 km^2
Number of solar farms required = 3540.31 km^2 / (300 MW / 36 MW/km^2) = 14

Percentage of California area consumed = 3540.31 km^2/ 423,971 km^2 = **0.84%**

Rooftop solar:

Rooftop solar requirement = 165.79 TWh/yr / (8760 h/yr) = 18.92 GW
Total area of roofs in California = 1.18 x 10^{10} ft^2

Capacity = 168 GW
Hence capacity > requirement, and land requirement = 0

Wind onshore	Quantity	Units
Average nameplate capacity of wind farm	1000	MW
Average CF of wind	0.243	
Land required	3461.637355	km^2
Percentage of California land area	0.82%	
Number of wind farms required	69	
Number of wind turbines required	23078	
Total Footprint	0.45	km^2
Wind offshore		
Avg. nameplate cap. of wind farm	3000	MW
Average CF of wind	0.62	
Land required	1356.738512	km^2
Percentage of California land area	0.32%	
Number of wind farms required	14	
Number of wind turbines required	4070	
Total Footprint	0.72	km^2
Utility-scale solar		
Avg. nameplate cap. of solar farm	300	MW
Avg CF of solar	0.33	
Land required	3540.310931	km^2
Percentage of California land area	0.84%	
Number of solar farms required	425	
Rooftop solar		
Total area of rooftops in California	1.18E+10	ft^2
Capacity	1.68E+05	MW

Table 4: Summary of resource allocation

Final Energy Mix:

It is assumed that no new hydroelectric or geothermal plants are added as part of the transition to a 100% WWS California. Given the existing infrastructure for hydroelectric and geothermal power, the following energy mix is finally arrived at.

Final Energy Mix (GW)	
Wind	41.45
Solar	61.28
Hydroelectric	0.32
Geothermal	1.51
TOTAL	104.57

Table 5: Energy mix in California in a 100% WWS world

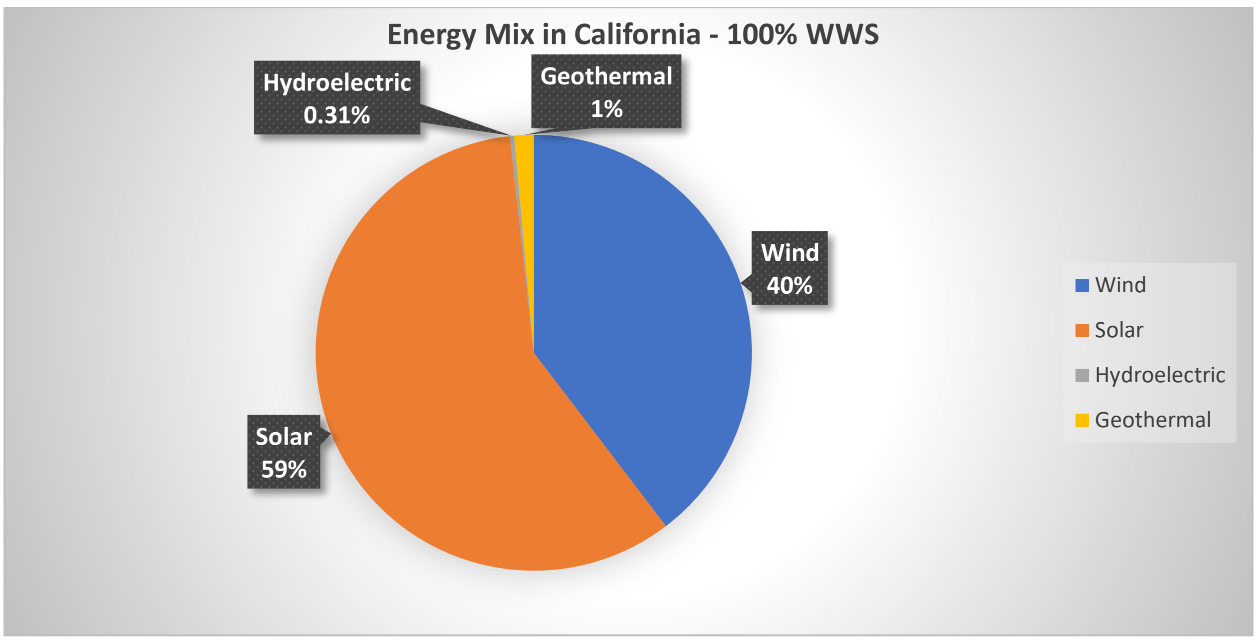

Figure 1: Energy mix in California in a 100% WWS world

<u>Policies to hasten the transition to a 100% WWS California:</u>

- Energy efficiency and building energy measures
- Energy supply measures
- Utility planning and incentive structures
- Transportation measures
- Industrial sector measures

<u>Conclusion – Benefits and challenges to reaching a 100% WWS world:</u>

A 100% WWS world offers several significant benefits:

- Environmental Sustainability: Renewable energy sources such as solar, wind, hydro, and geothermal power generate electricity without depleting finite resources or emitting greenhouse gases. This transition would significantly reduce carbon emissions, air pollution, and environmental degradation, contributing to mitigating climate change and preserving ecosystems.

- Energy Security and Independence: Relying on renewable energy sources enhances energy security by reducing dependence on fossil fuels, which are subject to price volatility and geopolitical tensions. Renewable energy is abundant, widely distributed, and can be harnessed domestically, promoting energy independence, and reducing vulnerability to supply disruptions.

- Economic Opportunities: The shift to renewable energy creates new job opportunities in manufacturing, installation, maintenance, and research and development sectors. It stimulates economic growth, spurs innovation, and attracts investments in renewable energy infrastructure, fostering a sustainable and resilient economy.

- Cost-effectiveness: Over time, renewable energy technologies have become increasingly cost-competitive with fossil fuels. With advancements in technology, economies of scale, and declining costs, a 100% WWS world has the potential to provide affordable and reliable energy in the long run, reducing reliance on expensive fossil fuel imports and volatile energy markets.

- Health and Well-being: By eliminating the pollution associated with fossil fuel combustion, a renewable electricity world would improve air quality, reducing respiratory illnesses and related healthcare costs. Cleaner energy sources contribute to healthier communities, enhancing overall well-being and quality of life.

- Energy Access and Equity: The transition to renewable energy can address energy poverty and promote equitable access to electricity. Renewable technologies can be deployed in remote and underserved areas, providing clean energy solutions to communities that previously lacked access to reliable electricity, empowering socio-economic development and reducing inequalities.

- Technological Innovation: The transition to a 100% WWS world drives research and development, encouraging technological advancements in energy storage, grid integration, and smart energy systems. These innovations have broader implications beyond the electricity sector and can revolutionize other sectors such as transportation, heating, and industrial processes.

Overall, a 100% renewable electricity world offers a sustainable, clean, and resilient energy system, mitigates climate change, enhances energy security, creates economic opportunities, and improves public health and well-being.

However, transitioning to a 100% WWS world faces several political and social barriers, including:

- Fossil Fuel Interests: The fossil fuel industry, which has a significant influence on politics and policymaking, may resist the transition due to economic interests. Fossil fuel companies may lobby against renewable energy initiatives, promote misinformation, or seek to maintain their market dominance.

- Policy and Regulatory Challenges: Inadequate or inconsistent policy frameworks, including the lack of supportive renewable energy policies, can hinder the transition. Political will and long-term commitment to renewable energy goals are necessary to overcome regulatory barriers and create an enabling environment.

- Resistance to Change: Transitioning to a renewable energy world requires significant changes to existing energy systems, which may face resistance from various stakeholders. This resistance can stem from concerns about job losses in traditional energy sectors, perceived risks or uncertainties associated with renewables, or reluctance to depart from familiar energy sources.

- Socioeconomic Impacts: The transition may have socioeconomic implications, particularly in regions heavily dependent on fossil fuel industries. Disruptions to local economies and communities can be a barrier if there is a lack of adequate planning and support for affected workers and communities. Addressing these impacts and ensuring a just transition is essential for social acceptance.

- Perception and Public Acceptance: Public perception and acceptance of renewable energy can influence the political will to transition. Concerns about the reliability, affordability, and aesthetics of renewable energy installations can create resistance. Effective communication, public engagement, and awareness campaigns are needed to address misconceptions and promote the benefits of renewable energy.

- Access to Finance and Investment: The transition to renewable energy requires substantial investments. Access to affordable financing and attracting private investments can be challenging, particularly in developing countries or regions with limited financial resources. Financial mechanisms and incentives are needed to facilitate the flow of funds into renewable energy projects.

- International Cooperation and Geopolitical Factors: The global nature of energy markets and geopolitical dynamics can present barriers to transitioning to a renewable energy world. Interactions between countries, including trade policies, energy dependencies, and geopolitical rivalries, can impact the pace and scale of renewable energy adoption.

Addressing these political and social barriers requires strong leadership, effective policymaking, stakeholder engagement, public awareness, and international collaboration. Overcoming resistance to change and ensuring a just transition are critical for achieving a sustainable and inclusive 100% WWS future by 2050.

References:

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4. Google Project Sunroof - https://sunroof.withgoogle.com/data-explorer/place/ChIJPV4oX_65j4ARVW8IJ6IJUYs/