TU Delft

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Integrating wind farms and electricity storage towards 2030 goal in California.

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The report is divided into 3 chapters, which are further subdivided into various paragraphs.

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INTRODUCTION

METHODOLOGY & RESULTS

CONCLUSION

Integrating wind farms and electricity storage towards 60% renewable energy electricity goal in California by 2030

PROBLEM STATEMENT

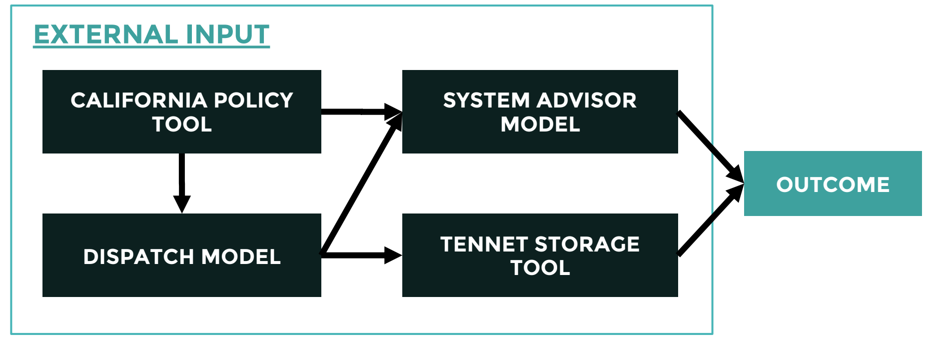
Background· The Californian government has set an ambitious target towards 2030· 60% of electricity is generated from renewable sources. However, there is huge gap between the current portfolio and required RES capacity, which indicates a huge investment potential.

Client· private investors, interested in wind farms and electricity storage

Outcomes·

- 2030 Energy scenario· fuel mix and capacity mix
- Hourly elec price projection with supply-demand dynamics
- Financial evaluation and suggestion of the RES project
- Investment suggestions and institutional implications

MODEL STRATEGY



INVESTMENT SUGGESTIONS AND INSTITUTIONAL IMPLICATIONS

	ΔELEC_PRICE	0%	+20%	+40%	+60%
Onshore wind farm	IRR [%]	2.20	3.74	11.88	19.23
	NPV [M$]	-499.07	-364.86	233.94	600.44
	-20% curtail	-374.30	-273.64	175.45	450.33
Electri-city storage	IRR [%]	4%	8%	11%	13%
	NPV [M$]	-11.7	-1.2	9.2	19.5
Combi-nation	NPV [M$]	-386.00	-274.84	184.65	469.83

Investment suggestion: There is no economical feasibility to invest either the wind farm or the storage under the predictive price scenario. What's worse, the potential curtailment impose a enormous impact on the revenue of the wind farm where on average NPV decreases by around 25% . When adjusting the price, the break-even points for both wind farm and storage occur between +20% and 40% . In addition, the introduction of electricity storage will mitigate the negative impact under high price scenarios (positive NPV), and it showcases that the integrated project is more profitable and attracting compared to any single investment.

Institutional implications: In terms of market design, to deal with the low marginal cost of RES, the capacity mechanism could be introduced to mitigate the private investment risk and maximize the supply reliability; From the authority side, more subsidies or public-private partnership could be implemented to support renewable energy and storage projects in order to accelerate energy transition.

California has set a 60% renewable electricity target by 2030.

SITUATION

- California has set a goal for 60 percent zero-carbon electricity by 2045.
- Currently, 34% of the electricity comes from renewable energy sources, with 9.4% nuclear, 46.5% natural gas, 11.3% Large hydro.
- The major renewables are Solar (14.0%), Wind (7.2%), Geothermal (5.9%), Biomass (3.0%), Small hydro (2.2%).

TRIGGER

- The transition towards 60% renewables has raised concerns regarding reliability requirements, resource adequacy and market economics.
- The redesign of the electricity network and market to accommodate increasing RES is costly and requires large investments.
- Congestion and volatile loading accompanying with fluctuating weather conditions are inevitable.

QUESTION

- What is the required generation portfolio to achieve the ambitious target in 2030 for California?
- What is the impact of RES penetration on the electricity prices and supply reliability?
- Is there any investment opportunity in term of Wind farms and Storage units?
- What are the policy recommendations to empower the transition?

PROBLEM STATEMENT

Towards 2030, the Californian government wants to reach at **least 60%** of all energy originating from renewable sources. Our client (problem owner), a **private investor**, is interested in investing in **wind power plants and electricity storage** in the form of batteries. By combining knowledge from both policy models, technical models and financial evaluation models, we aim to provide our client with **advise** on possible investment opportunities for in the sector. The proposed modelling strategy is depicted below.

Four models are closely and strategically coordinated to address the research question.

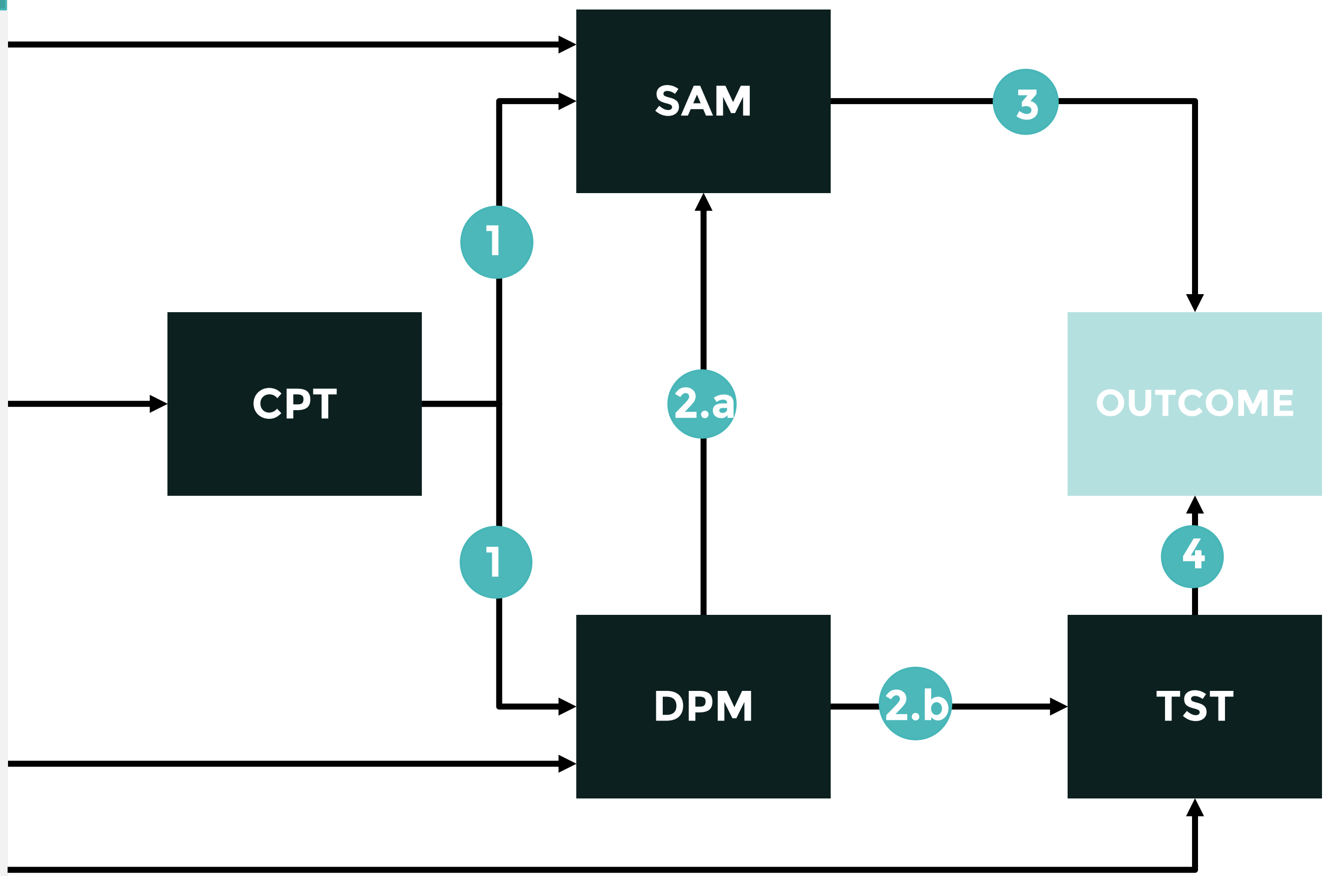
EXTERNAL INPUT

SYSTEM ADVISOR MODEL (SAM)
- Reference weather data
- Forecasted turbine specifics

CALIFORNIA POLICY TOOL (CPT)
- California RES target
- Potential policy interventions

DISPATCH MODEL (DPM)
- Hourly system demand
- Renewables availability
- Generation cost
- Technology characteristic
- Capacity mix

TENNET STORAGE TOOL (TST)
- Storage capacity
- Technical characteristic



LEGEND

MODEL

FINAL OUTPUT

1 **OUTPUT CPT**
- 2030 prediction required generation capacity

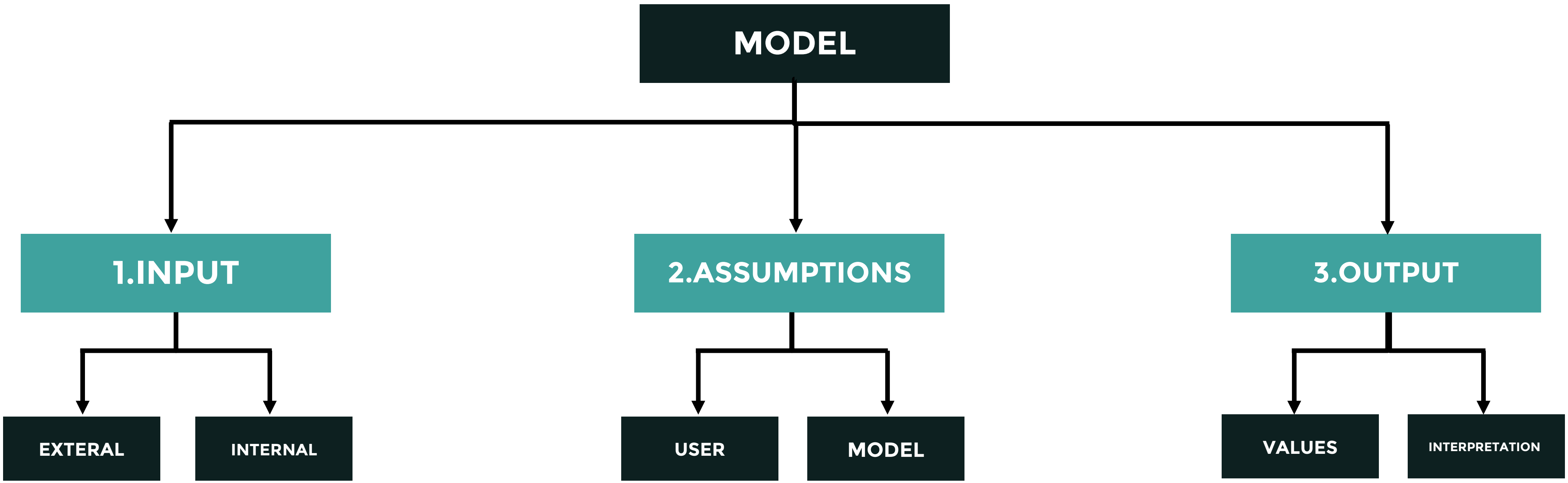
2.a **OUTPUT DPM**
- Average price

2.b **OUTPUT DPM**
- Hourly electricity price
- Power shortage and curtailment

3 **OUTPUT SAM**
- LCOE
- Net present value
- Internal rate of return

4 **OUTPUT TST**
- Net present value
- Internal rate of return

Each model will be dissected into roughly three paragraphs clarifing the input, assumptions and output.



COMMENTS

In order to dissect the utilised models, for each we broadly specified (1) the input, (2) the assumptions and the (3) output. These three paragraphs, are further subdivided as depicted in the graph above. For paragraph 1, both the external and internal values will be elaborated upon. The external input refers to the values retrieved from various sources of literature and data which were needed to run the models. The internal input refers to values retrieved from other models used within this project. With regard to the assumptions both the assumptions made by the model and the user of the model will be clarified. Finally, the output values will be presented and explained.

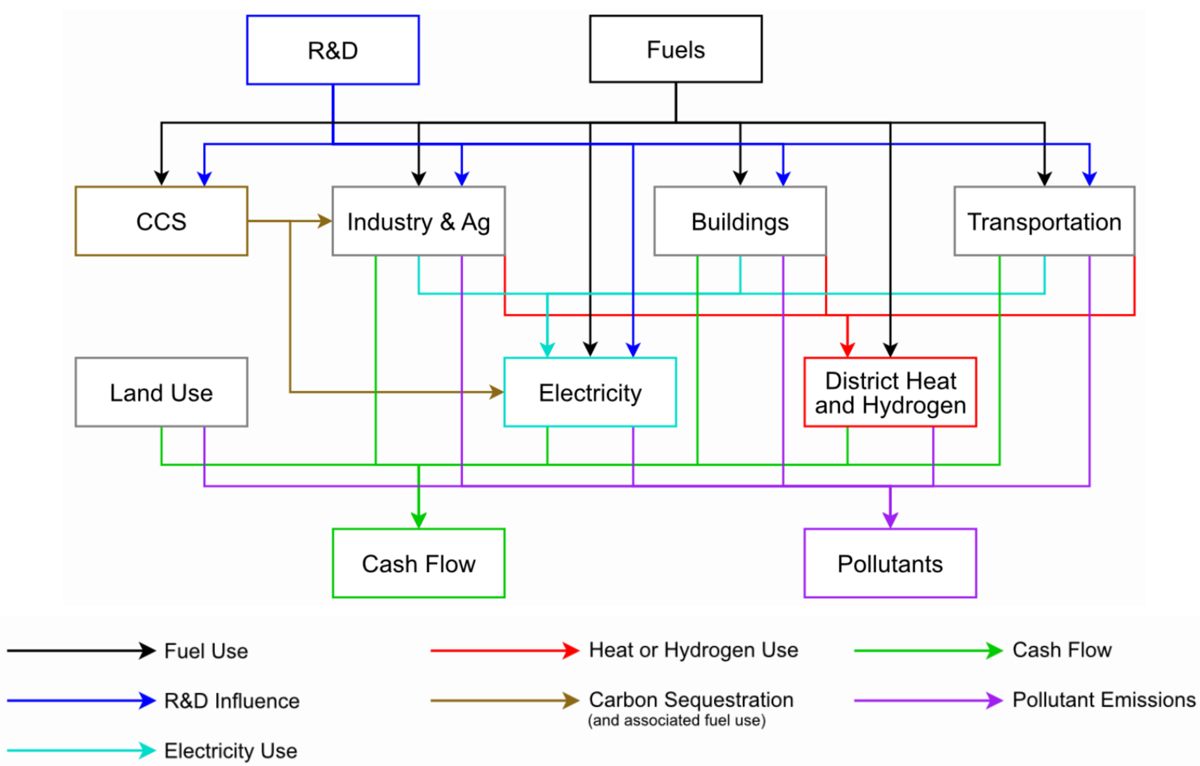
CPT explores the effect of various policy settings on GHG emissions and Renewable Energy Target.

CALIFORNIA POLICY TOOL (CPT)

DESCRIPTION	California Policy Tool allows user to control a wide variety **different policies** that affect **energy use and emissions** in various sectors of the economy (such as a carbon tax, demand response, fuel economy standards for vehicles, reducing methane leakage from industry, and accelerated R&D advancement of various technologies). The model includes every major sector of the economy· transportation, electricity supply, buildings, industry, agriculture, and land use.
RATIONALE	In this report, California Policy Tool is used for 2 main purposes. First, it **predicts electricity generation** in 2030 which is further used by Dispatch Model. Second, it **explores the effect** of few policies and make recommendations to achieve 60% electricity from renewables by 2030 popularly known as Renewable Portfolio Standard in California.
APPROACH	The model has a **base case scenario also known as BAU(business-as-usual)** scenario which predicts the electricity generation in 2030 as a result of on-going policies being followed in California. This generation and capacity mix serves as an input to the Dispatch model. Furthermore, various policy levers viz. subsidies, carbon tax, grid scale battery storage, clean energy standard and their combinations are explored to see **their effect on the renewable energy portfolio of California in 2030**. Corresponding effect on GHG emissions, cash flows, levelized cost, renewable curtailment is also studied to support the recommendations. Any new policies chosen by the user are not a replacement but an addition to the policies that are in place in BAU scenario

CPT is a dynamic computer model created in Vensim using variables to compute electricity requirements.

MODEL DIAGRAM



COMMENTS

- The model **uses "stocks" or variables** whose value is remembered from timestep to timestep and the output of the previous timestep serves as an input of the following timestep.
- Arrows in the adjacent diagram denote the order of calculation. For example, the amount of electricity required is calculated in the demand sectors (Industry, Buildings, Transportation) , and then this result is fed into the Electricity Sector, which determines how to generate the necessary quantity of electricity.

These policies were used as an external input to the CPT to evaluate their effectiveness in realizing the RPS target.

EXTERNAL INPUT		
ITEM	**DESCRIPTION**	**SOURCE**
SUBSIDIES ON WIND, SOLAR PV, SOLAR THERMAL AND BIOMASS	These denote the subsidy paid by the government to suppliers of electricity per unit of electricity generated from onshore wind, solar PV, solar thermal and biomass	• California Pathways Model, Lazard's Levelized Cost of Energy Analysis
GRID BATTERY STORAGE CAPACITIES	This specifies grid-scale electricity storage from chemical batteries to grow at the specified percentage, annually, above the amount predicted in the BAU Scenario.	• California Public Utilities Commission
CLEAN ENERGY STANDARD	It specifies an increase in the fraction of RPS. RPS requirements are met by electricity suppliers through a system of tradable renewable energy credits (RECs), with each MWh of generation assigned a unique tracking number. Using a credit system allows suppliers lacking adequate renewable resources to purchase credits rather than investing in renewable generation of their own, helping to minimize the overall cost of compliance. Non-complying suppliers are penalized.	• California Public Utilities Commission , Senate Bill 100
CARBON PRICING	It specifies a price applied on fuels used in the Electricity Sector based on their greenhouse gas emissions.	• California Cap and Trade Program

Renewable Portfolio Standard equal to 60% serves as a target for all the policy designs. California government sets continuously escalating renewable energy procurement requirements for the state's load-serving entities

Various assumptions are made for different sectors and variables pertaining to these sectors.

ASSUMPTIONS

RENEWABLE PORTFOLIO STANDARD

- Tool calculates RPS required % as a function of generation. The state policy applies to sales. We adjust to account for the somewhat smaller requirement after transmission losses.
- It currently supports very high levels of zero carbon electricity, but the last few percentage points of the transition are beyond current scope. For this reason, the model does not eliminate natural gas peaker plants, currently.
- It does not account for small hydro which, for the purpose of this project, has been added explicitly based on California Energy Commission data.
- Because of the mismatch between the model structure and California realities, some calibration of the final values was carried out. Essentially, increments were added and subtracted to arrive at a value that serves as an approximation of the 60% RPS level in 2030

FUELS AND POWER PLANTS

- Coal is retired over 4 years.
- All steam turbines are nonpeaking natural gas plants.
- Combustion turbines are natural gas peakers.
- Dispatch priority 1 to zero carbon resources, natural gas peaker and petroleum-fired plant have priority 2 and others have priority 3.

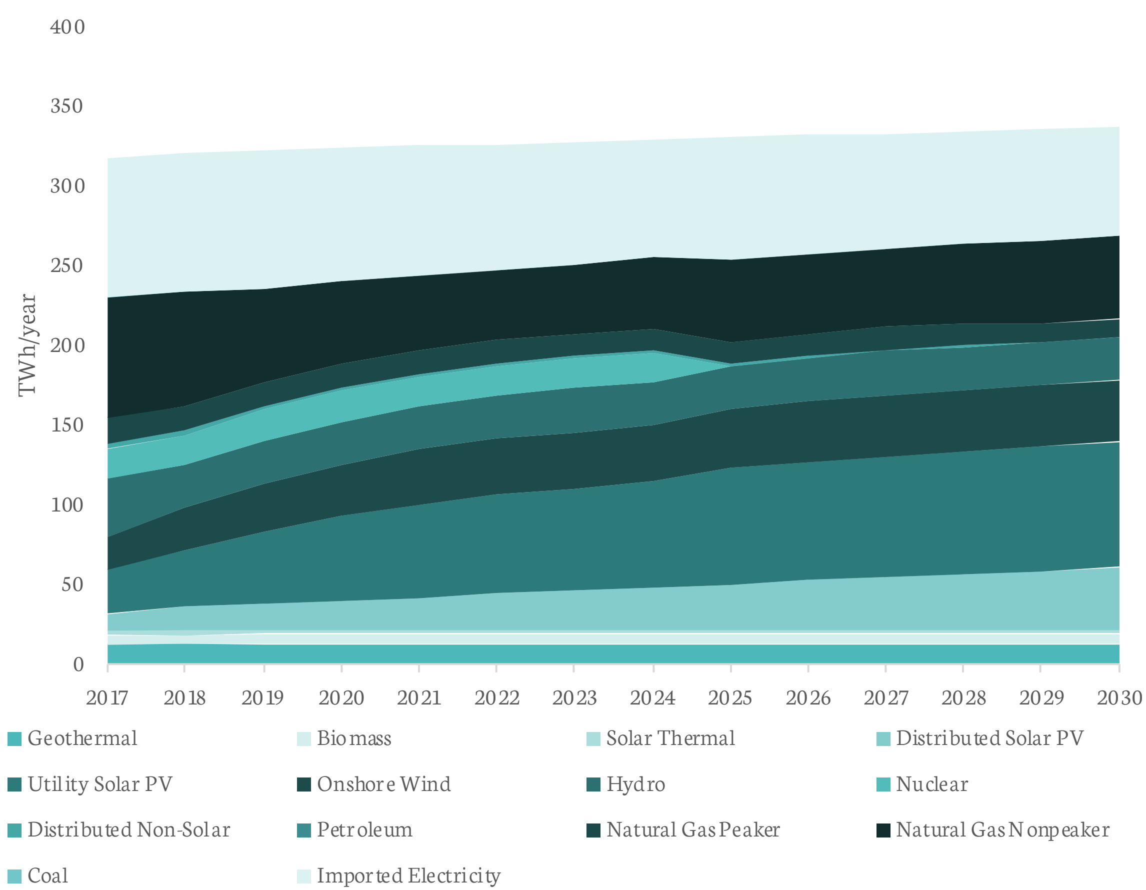
SOLAR, WIND AND HYDRO

- Wind and Solar PV are handled differently in the model, relying on endogenous, capacity-based learning curves to determine cost declines.
- For hydro, it is very difficult to build new conventional hydro due to environmental concerns and permitting requirements.
- Curtailment from wind is assumed to be zero

BAU scenario predicts generation and capacity mix in 2030 as a result of on-going policy efforts.

OUTPUT: 2030 SCENARIO

Generation mix – BAU scenario



Capacity mix 2030

SOURCE	2020	2030
Geothermal	2.734	2.734
Biomass	1.324	1.324
Solar Thermal	1.249	1.249
Distributed Solar PV	10.111	21.166
Utility Solar PV	26.944	40.13
Onshore Wind	12.53	14.705
Hydro	13.992	13.992
Nuclear	2.393	0
Distributed Non-Solar	0.456232	0.095897
Petroleum	0.355	0.355
Natural Gas Peaker	11.944	8.96104
Natural Gas Nonpeaker	28.8789	24.761
Coal	0.012	0
Total	112.923	129.472

- Energy transition roadmap to 2030 with predictive generation capacity and fuel mix· the 60% RES target is achieved in the form of 23.3% Utility Solar PV, 11.5% Onshore wind, 11.7 % distributed solar, 3.65% Geothermal and 1.93% Biomass, accompanying with the phase out of coal and nuclear plants.

Exploring the effect of subsidies, storage and other policies on the Renewable energy mix and CO2 emission.

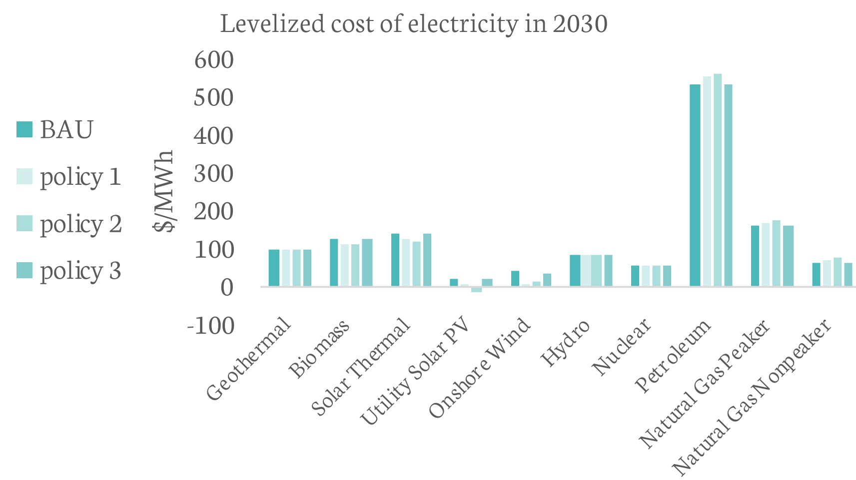
INPUT

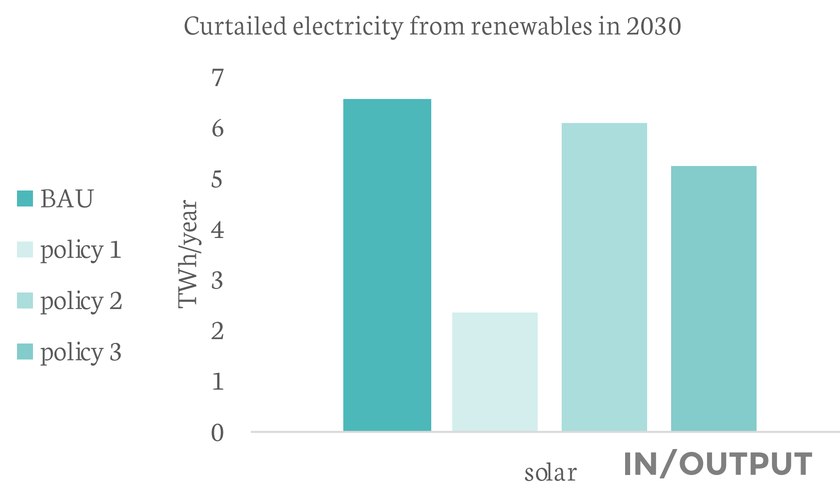
POLICY LEVERS	POLICY 1	POLICY 2	POLICY 3
Grid scale electricity storage	5.50%	5.50%	5.50%
Onshore wind subsidy ($/MWh)	Variable(18 -40)	25	3
Solar PV subsidy ($/MWh)	14	Variable (14-40)	NA
Solar Thermal subsidy ($/MWh)	14	20	NA
Biomass subsidy ($/MWh)	14	14	NA
Carbon Pricing ($/MMT) CO2e)	25	25	NA
Clean Energy Standard	NA	NA	6%

OUTPUT

POLICY	RENEWABLE % IN GENERATION MIX (2030)
Policy 1	61%
Policy 2	61%
Policy 3	67%

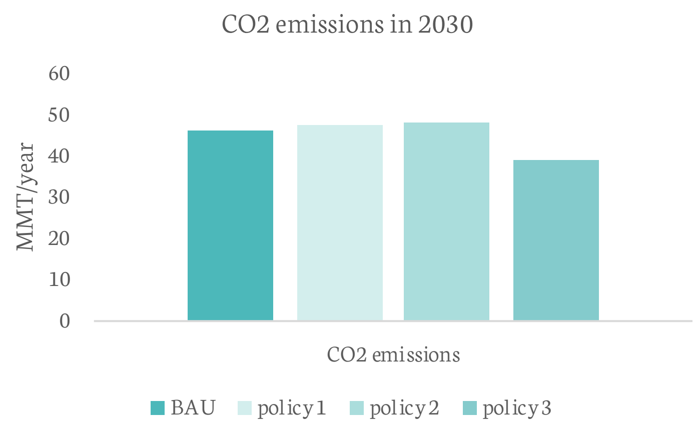
OUTPUT

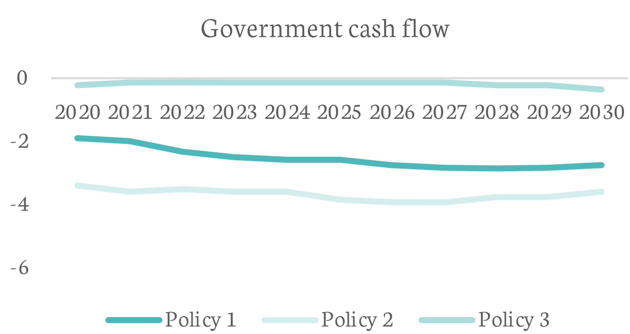




Exploring the effect of subsidies, storage and other policies on the Renewable energy mix and CO2 emission.

OUTPUT: 2030 SCENARIO





INTERPRETATION

- Huge subsidies on renewables will result in high government spending. Moreover, subsidies for biomass, solar thermal do not result into higher generation from these sources. In that case, they bring down the levelized cost of the electricity from these resources. (Policy 1 and 2)
- Carbon pricing coupled with subsidies is not enough to reduce GHG emissions. New innovative ways have to be used to reduce GHG emissions. (Policy 1 and 2)
- Storage facilities can significantly reduce curtailment and hence present a business opportunity in all scenarios.
- Strategy used in policy 3 can achieve the target and be most cost efficient for the government. Hence approach used in policy 3 can be thought of as an alternative to conventional policies.

**More information on the policies is available in the appendix*

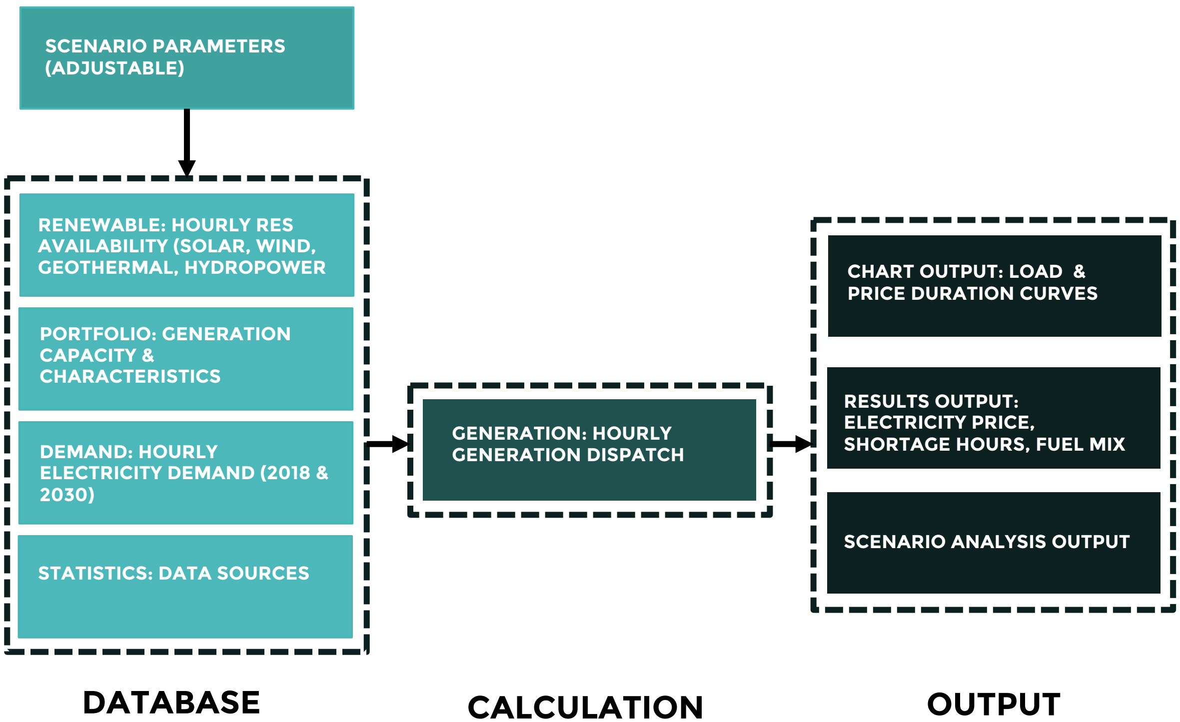
The DPM is developed to explore the impact on the electricity price in 2030 energy scenario.

DISPATCH MODEL (DPM)

DESCRIPTION	The dispatch model explores the electricity price change and supply reliability with **increasing renewable energy** (mainly solar & wind), and coordinates **with TenneT storage and SAM** to perform the **investment analysis** for wind turbine and electricity storage.
RATIONALE	In this report, the dispatch model is used as a **prediction tool** for electricity market in 2030. The key output -- hourly electricity clearing price is served as the **main input/revenue** for the financial evaluation for the wind turbine and storage. Besides, hourly **power shortage or curtailments** could be derived to indicate the supply reliability with the high renewable energy penetration.
APPROACH	The fundamental principle of modelling is to meet the hourly demand **with the least-cost generation technologies**. The predictive generation capacity in 2030 from California Policy Model serves as the input portfolio for the Dispatch model. Besides, hourly system demand, renewables hourly availability, generation cost, 10-technology characteristic data are embedded in the model to calculate the **expected market clearing price and other indicators such as power shortage and curtailment**. Excel is used to perform such functions with simplified setting for the real market. The hourly price is used in the TenneT storage model to conduct the operation optimization, and the PPA price in the SAM model is set as the average price of the whole year.

The DPM classified into Database, Calculation, Output sheets as well as Scenario parameters for adjusting.

MODEL DIAGRAM



COMMENTS

- The database sheets include all the collected data and sources to serve as the input and for comparison
- The generation sheet is to perform the hourly dispatch to calculate the electricity production for each technology
- The output sheets demonstrate the main charts and indicators, e.g. demand and price duration curves, energy mix, etc .
- The scenario analysis focuses on various transition efforts with different Solar PV and wind farm capacity

The input data is derived from California Policy Model results, official statistics and credible literature.

INPUT

NAME	VALUE	SOURCE
1. HOURLY SYSTEM DEMAND 2018 & 2030 FORECAST	The hourly demand distribution is calculated based on the CAISO - TOTAL TAC Area in the Day ahead market. The model only considers the in-state demand and generation portfolio. So the built-in demand data is calculated by multiplying in-state yearly generation and hourly distribution.	• OASIS - OASIS Prod - PUBLIC • Workshops for 2017 Integrated Energy Policy Report
2. CAPACITY MIX 2018 & 2030 FORECAST	10 main generation technologies are chosen including Solar, Wind, Hydro, Geothermal, Nuclear, Biomass and four gas plants.	• Electric Generation Capacity & Energy • California Policy Model (2030 Scenario)
3. FUEL PRICE & GENERATION COST	The 2030 Mid Scenario in the ATB dataset is used in the model. The marginal cost is set the sum of fuel cost and variable O&M cost, which is assumed as the bidding price.	• Estimated Cost of New Utility-Scale Generation in California· 2018 Update • Annual Technology Baseline (ATB) Data
4. RENEWABLE FLUCTUATED AVAILABILITY	The hourly Solar availability is set as the average value from 2005 to 2015. The hourly Wind data is obtained from the SAM weather file. As for hydropower, a monthly variation is considered in line with history data from 2011 to 2019.	• Photovoltaic Geographical Information System (PVGIS) • System Advisor Model (SAM)· Home • EIA-CALIFORNIA RENEWABLES DATA
5. ACTUAL ELECTRICITY PRICE 2018	The daily day-ahead wholesale electricity prices during peak hours at CAISO SP-15 is utilized to compare with the model results and validate the accuracy.	• U.S. Energy Information Administration

Fixed dispatch priority and fluctuated availability factor are assumed to simplify the actual situation.

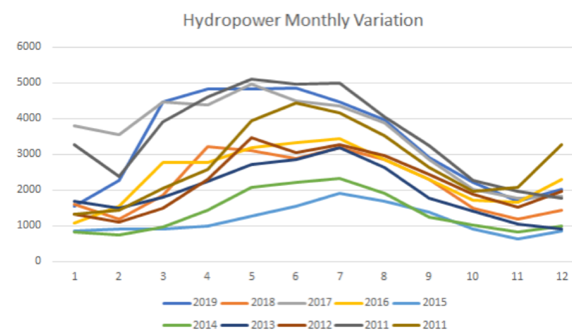
ASSUMPTIONS

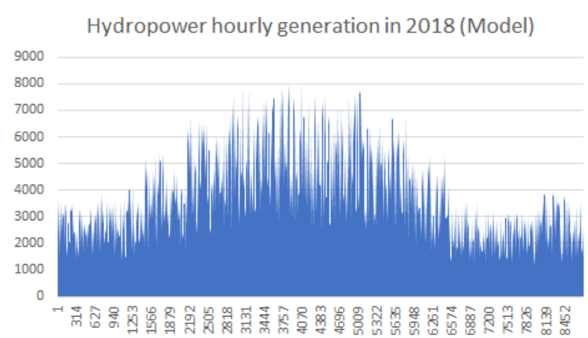
FIXED DISPATCH PRIORITY

#	Type	MC ($/MWh)
0	Solar	0
0	Wind	0
0	Hydro	0
0	Geothermal	0
1	Nuclear	9
2	Gas-CC	29
3	Biomass	35
4	Gas-CC-High	39
5	Gas-CT	44
6	Gas-CT-High	59

- The dispatch order is fixed In term of the Marginal cost from the lowest to the highest.
- No storage, no ramping limit
- The market clearing price is equal to the marginal cost of the last operation unit.

FLUCTUATED GENERATION





- A random availability factor is introduced to simulate the hourly generation fluctuation.
- Take the geothermal as an example. The availability factor is set as 60% based on the average yearly generation over capacity*hours from 2009 to 2018. Thus, the hourly available capacity ranges from 0.2 to 1.0 times capacity.
- As for hydropower, a monthly variation is considered in line with history data with a random hourly availability factor from 0.5 to 1.5 to simplify the actual uncertainty.

The 2018 case is utilized to validate the applicability and accuracy of the dispatch model.

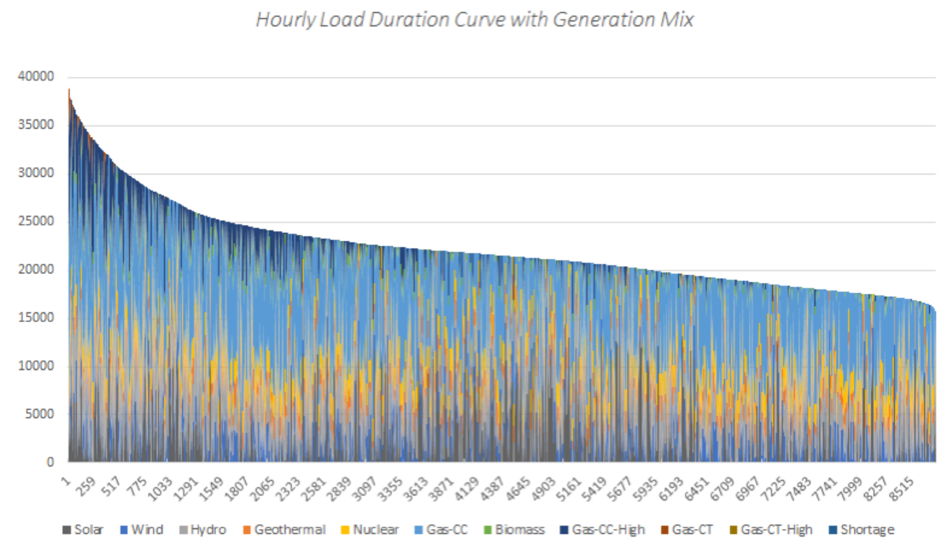
OUTPUT: MODEL VALIDATION:2018 SCENARIO

GENERATION FUEL MIX

POWER PLANT	POWER MIX	2018 ACTUAL MIX
Solar	13.4%	14.0%
Wind	8.6%	7.2%
Hydro	16.5%	13.5%
Geothermal	7.2%	5.9%
Nuclear	9.8%	9.4%
Biomass	1.8%	3.0%
Natural gas	42.8%	46.5%
	MODEL PRICE	**ACTUAL PEAK PRICE***
Mean	31.56	47.36
Standard deviation	8.20	31.89

**Daily day-ahead wholesale electricity prices during peak hours at CAISO SP-15*

DURATION CURVE



- The model results are consistent with the actual value in term of fuel mix and wholesale price
- Price spikes occurs in summer time (Jul.--Aug.)
- No power shortage due to the abundant back-up gas plant

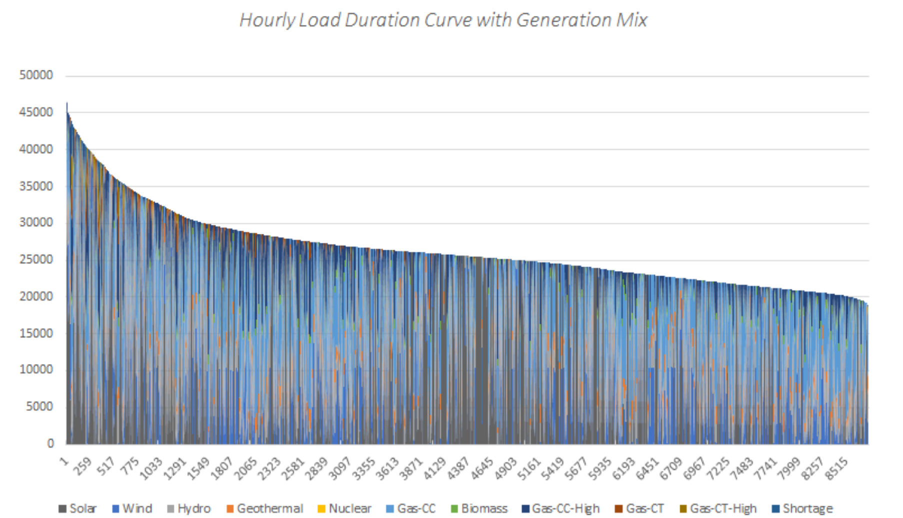
The 2030 Scenario is studied using the predictive capacity from CPM.

OUTPUT: 2030 SCENARIO

TYPE	CAPACITY	POWER MIX	CAPACITY FACTOR	2018 DATA
Solar	40130	31.4%	0.83	1.00
Wind	14710	14.0%	0.79	1.00
Hydro	13990	10.6%	0.76	1.00
Geothermal	2730	4.6%	0.73	0.98
Nuclear	0	0.0%	N/A	0.96
Gas-CC	12380	25.1%	0.64	0.74
Biomass	1320	2.1%	0.50	0.39
Gas-CC-High	12380	11.2%	0.27	0.11
Gas-CT	4480	0.8%	0.05	0.00
Gas-CT-High	4480	0.3%	0.02	0.00

**Daily day-ahead wholesale electricity prices during peak hours at CAISO SP-15*

DURATION CURVE



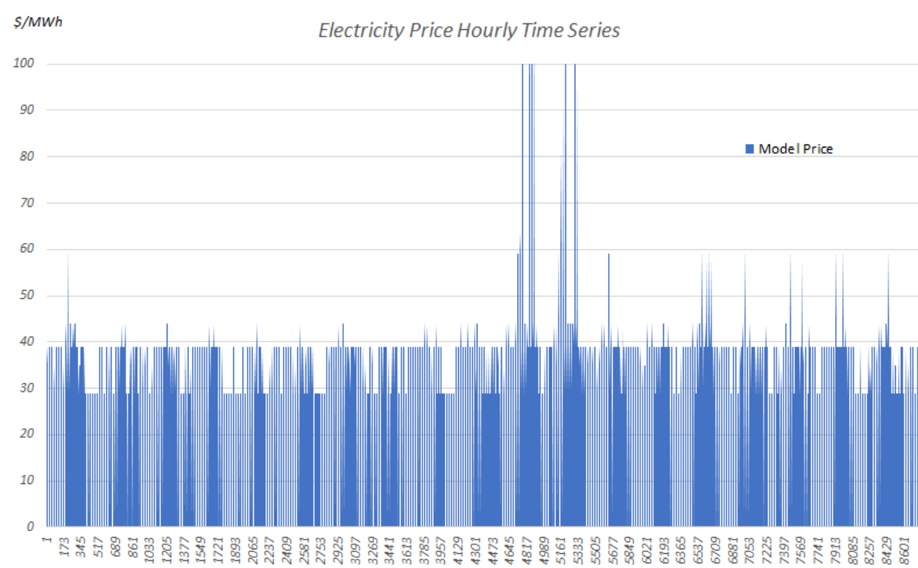
- Renewable energy electricity accounts for 52% in total
- However, huge renewable curtailment occurs, 22% in average 21.5% for Solar, Wind and Geothermal
- For controllable gas plants, the capacity factor remains relatively stable with the phase out of some plants

The average electricity price drops by 10% accompanying with increasing fluctuation and power shortage.

OUTPUT: 2030 SCENARIO

ITEM	MODEL PRICE
Mean	28.40
Standard deviation	25.12
Max	250
Min	0

POWER SHORTAGE	
Hours	83
Amount	241799 MWh



COMMENTS

- Demand price elasticity is introduced as -0.1 $/MWh per MW with a price cap of 250 €/MWh
- The average price decrease by 10% compared to that in 2018, but with higher fluctuation due to the weather dependency of renewables and decreasing back-up capacity (gas plants)
- Both power shortages and curtailment emerges with decreasing supply reliability, which indicates the necessity of electricity storage

SAM models the performance and economics for both land-based and offhsore windfarms.

SYSTEM ADVISOR MODEL (SAM)

DESCRIPTION	SAM's Wind Power model is a software tool developed by the National Renewable Energy Lab (NREL) that models the **performance and economics** of renewable energy projects. For our project two large-sized centralized (land-based and offshore) wind farms are modelled and investigated.
RATIONALE	In this report SAM is used as a decision-making tool to advice the problem owner. SAM provides an overview of the the **monthly energy production** and the **levelized cost of electricity** (LCOE). The LCOE can be defined as the total project lifecycle cost expressed in ¢/kWh of electricity generated by the wind farms. Both metrics combined can be used to **compare** the cost and performance of offshore and land-based wind farms is California. In addition SAM is used to determine the net present value (NPV) and internal rate of return (IRR) for both types of wind farms.
APPROACH	First, the **wind resource** is characterized through an hourly data file. Secondly, the wind turbine's power curve is defined through its **technical characteristics**. Thirdly, the windfarm layout and associated wake effect losses are defined. Lastly, the electrical output of the wind farm is calculated in kWh for 8760 hours. In addition a **sensitivity analysis** is executed to determine the net present value (NPV) and the Internal rate of return (IRR) for the wind farm for varied values of the power purchase agreement (PPA) price. The base value for the sensitivity analysis is retrieved from the Dispatch Model.

The external input values were used to determine the technical characteristics of the forecasted windfarms.

EXTERNAL INPUT (1)

External input data is needed to describe the performance characteristics of physical equipment within the two windfarms. Additionally, project costs and financial assumptions are required to determine the LCOE. The section that follows gives an extensive overview in which each input value is defined .

NAME	VALUE	SOURCE
1. WIND RESOURCE	The SAM weather file is a text file containing data on wind speed, direction, air temperature, and air pressure. For this project reference data for both **offshore Northern California**, and **land-based Southern California** is used to determine the performance and economics for both types of wind farms.	• Reference Manual for the System Advisor Model's Wind Power Performance Model. (Freeman & Jorgensen, 2014)
2. WIND TURBINE	The parameters for the wind turbine consist of the rated output, the rotor diameter and the hub height. The hub height expresses the height of the rotor above sea-level. Together they describe the turbine power curve of the wind turbine. For this research the rated output is chosen as **10 MW** with a corresponding rotor diameter of **205m** and a hub height of **214m**. These values were adopted from Musial et. al (2016).	• Potential Offshore Wind Energy Areas in California: An Assessment of Locations, Technology, and Costs (Musial et al., 2016)

The external input values were used to determine the technical characteristics for the windfarm.

EXTERNAL INPUT (2)

NAME	VALUE	SOURCE

3. SYSTEM COSTS

The system costs specify the costs associated with both wind farm projects. The system costs are divided into **(1) capital costs and (2) operation and maintenance costs**. The capital cost are further subdivided into turbine costs and balance of system (BOS) costs. Based on the literature, the following values have been identified.·

	Land-based	Offshore
Turbine Costs	9,305,468.00 $/turbine	1557 $/kW
Balance of System Costs	166.64 $/kW	12685 $/kW

- Wind Turbine Design Cost and Scaling Model. (Fingersh, M. Hand, and A. Laxson, 2006)
- Cost of Wind Energy Review. (Stehly, Beiter, Heimiller, and Scott, 2017)

The internal input values are attained from the California Policy Tool and the Dispatch Model.

INTERNAL INPUT

Internal input data is also needed to describe the performance characteristics of physical equipment within the two windfarms. The modelling strategy was structured such that certain output values from other models were needed to run others . The section that follows gives an extensive overview in which each input value is defined .

NAME	VALUE	SOURCE
1. WINDFARM	The windfarm specifics were retrieved from **the California Policy Tool**. According to the existing wind farm projects in California, 2000 MW is chosen to be the baseline capacity. This corresponds to 200 wind turbines within SAM.	• California Policy Tool
2. REVENUE	The revenue of the windfarm is retrieved from the dispatch model. According to the developed model the **power purchase agreement** (PPA) price is set at **2.84 ¢/kWh.** This value is used as input to determine the revenue in the SAM.	• Dispatch Model

The assumptions in the SAM can be subdivided into user assumptions and model assumptions.

ASSUMPTIONS

USER

1. WIND RESOURCE

The reference files embedded in SAM are considered to be **representative** as they reflect the wind resource over a period of 14 years (1996-2010).

2. WIND FARM

The wake effects within the wind farm are modelled according to a **simple wake model**, which uses a thrust coefficient. The thrust coefficient determines the speed losses for each turbine. The simple wake model is assumed to be representative as the windfarm array is "simplistic" as does not take into account different patterns.

3. WIND TURBINE

The annual degradation is set at 0.5. This value has been adopted from Staffel and Green (2014). Additionally, with regard to the offshore wind farms **semisubmersible** has been chosen as the substructure type. This option was selected as the majority of the papers reflecting on California's offshore wind potential utilised this structure.

MODEL

1. WIND TURBINE

The model assumes that each wind turbine within a farm is located at the same height above sea level. More specifically, the wind turbines within the wind farm cannot be configured individually.

2. WIND FARM

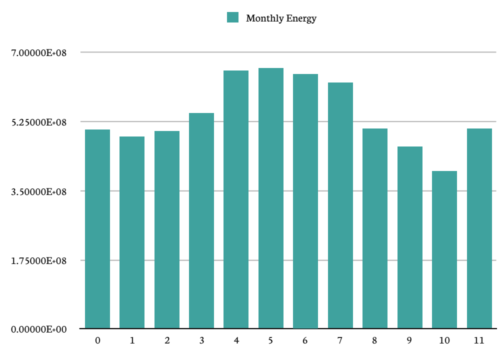
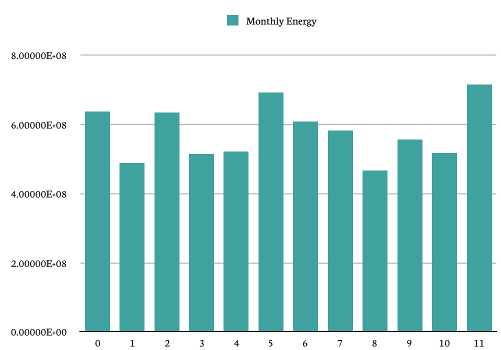
The model assumes that the terrain set in the weather resource tab is the same throughout the windfarm as whole. Hence it is not allowed to create one windfarm stretching over different terrains.

SOURCE

- How does wind farm performance decline with age? (Staffel & Green 2014)

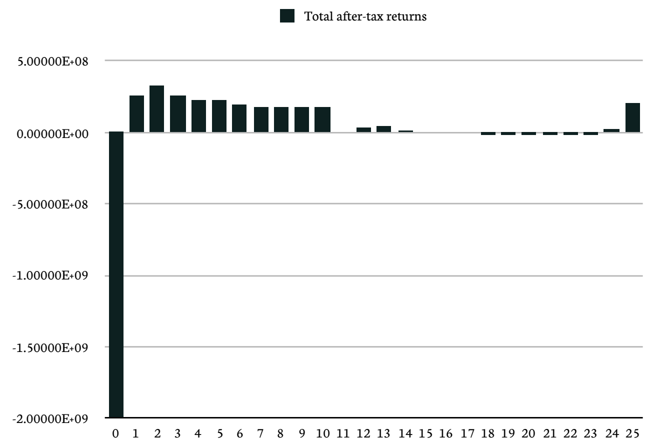
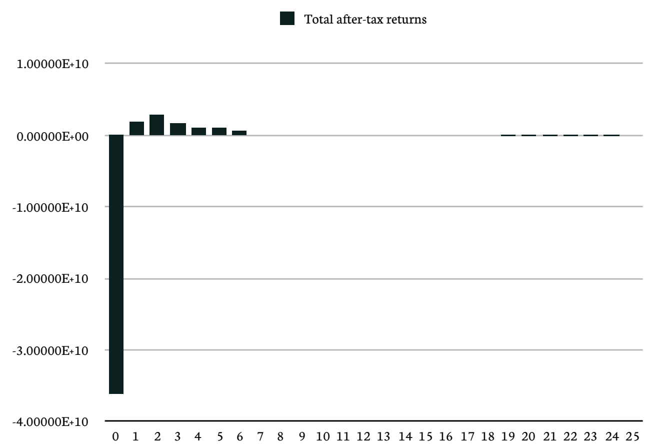
Based upon the input values, SAM produces the monthly energy for the designed windfarms.

OUTPUT(1)

NAME	VALUES & FIGURES		INTERPRETATION
1. LAND-BASED ENERGY PRODUCTION		**Capacity factor** 37.1% **LCOE** 3.05 ¢/kWh	• The monthly energy graphs illustrate the monthly energy production of the land-based wind farm located in Southern California and the offshore wind farm located in Northern California. As can be seen from the graph the production reaches peaks in May, June, July and August. This can be explained as the average **wind speeds reach its maximum** during these months. • In addition, the capacity factor and LCOE are indicated for both types of windfarm. The significant difference in LCOE can be explained as the the total costs of building and operating a generating the offshore windfarm during its lifecycle is substantially higher.
2. OFFSHORE ENERGY PRODUCTION		**Capacity factor** 39.6% **LCOE** 37.52 ¢/kWh	

The cashflow for both wind farm projects illustrate the the NPV after 25 years.

OUTPUT(1)

NAME	VALUES & FIGURES	INTERPRETATION
1. LAND-BASED CASH FLOW		• The cashflow graphs for both land-based and offshore show a large negative number in year zero, which indicates the high initial cost. It is evident that the investment cost of the offshore windfarm is significantly higher as the technologies and installation cost are much more complex. This downward peak is followed by income generated from accelerated depreciation. Following this period, we notice the operating costs in the out-years. From both graphs it is clear that the both powerplants do not receives enough income to recover the initial costs.
2. OFFSHORE CASH FLOW		

A sensitivity analysis was performed for various levels of the PPA price to study the effects on NPV and IRR.

OUTPUT(2)

NAME	VALUES & FIGURES	INTERPRETATION

SENSITIVITY ANALYSIS PPA PRICE FOR LAND-BASED WIND FARM.

PPA Price($/kWh)	IRR (%)	Net Present Value ($)
0.01704	NaN	-1.23207E+09
0.02272	-2.08598	-8.65572E+08
0.0284	2.19982	-4.99069E+08
0.03048	3.74407	-3.64856E+08
0.03976	11.8797	2.33937E+08
0.04544	19.2251	6.0044E+08

SENSITIVITY ANALYSIS PPA PRICE FOR OFFSHORE WIND FARM.

PPA Price($/kWh)	IRR (%)	Net Present Value ($)
0.01704	NaN	-2.93598E+10
0.02272	NaN	-2.89994E+10
0.0284	NaN	-2.8639E+10
0.03048	NaN	-2.85071E+10
0.03976	NaN	-2.79183E+10
0.04544	NaN	-2.7558E+10

- Both tables highlight the sensitivity analysis performed with the price of the PPA varied in size simulations up to a 60% increase in price. The range taken for the PPA price is as follows [-40% ,-20% ,0,20% ,40% ,60%]. The values have been chosen as on average the windfarm will have a curtailment of 20% , which means that -20% NPV price is the base case scenario.
- The most right column indicates the NPV associated with the various values of the PPA price.

The TenneT Storage Tool is used to determine the financial feasibility of an electricity storage project.

TENNET STORAGE TOOL

DESCRIPTION

The TenneT Storage Tool is a financial evaluation tool for electricity storage projects. The tool has been developed by TenneT, the Dutch TSO. The tool is used to predict the financial feasibility of battery storage projects. For this assignment, three different sizes of Lithium-ion batteries have been investigated for the years 2018 (base-year) and 2030.

RATIONALE

In this project, the TenneT Storage Tool has been used to give advice to the problem owner with regard to the battery project parameters. The tool optimizes charging and discharging of the battery according to price data, gathered from the dispatch model that has been used for this project. The output of the tool consists of many financial indicators with the most important ones being the yearly revenue, yearly cash flow and the net present value of the project in M$. With these indicators, the financial feasibility of the project can be determined.

APPROACH

First, the technical and financial input data is implemented in the project's formulae. Second, the hourly dispatch model is used to optimise the revenue from charging and discharging over the entire year. This means that the model assumes perfect information for that year's prices in advance. Then, the model calculates the financial flows for every year of the project's economical lifetime. These calculations result in the financial indicators mentioned above. Finally, these financial indicators give the modeller insight into the project's feasibility. After which the modeller is able to construct advice for the problem owner, regarding that specific project.

The following external input data was used to determine the project parameters.

EXTERNAL INPUT (1)

The external input data is needed to enable the tool to optimize the project's revenue according to the preferred parameters. Additionally, the price data from the dispatch model was used to ensure that the optimization was conducted over the investigated period of time. The section below provides an extensive overview in which each input value is defined.

NAME	VALUE	SOURCE
1. TECHNICAL CHARACTERISTICS	The TenneT storage tool requires technical input from the modeller in order to be able to calculate a project's feasibility. the technical data allows the modeller to model the differences in technology over the course of time. By setting all technical parameters equal for all model runs in the same year, an insight in the feasibility of the various sizes of projects emerges. Main technical parameters are the ramp rate, availability, round trip efficiency, and maximum number of full cycles.	• Technology Overview on Electricity Storage. (Sauer, D.U., Leuthold, M., Fuchs, G. & Lunz, B., 2012)
2. FINANCIAL CHARACTERISTICS OF BATTERY	In order to calculate the financial feasibility of the storage project, data on the costs of battery storage is required as input data. These data parameters are used to determine the overall yearly cost of the project. Together with the revenue, the net present value of the project can be determined. The most important financial input parameters are the capital expenditures, debt rate, economic lifetime	• State taxes (San Francisco Office of the Mayor, San Francisco Office for Economic and Workforce Development, San Francisco Office of Small Business, & San Francisco Department of Technology. 2020)

The following external input data was used to determine the project parameters.

EXTERNAL INPUT (2)

NAME	VALUE	SOURCE
3. DISPATCH MODEL	In order for the TenneT Storage Tool to determine the buy and sell strategy of the battery, the tool requires electricity prices. These electricity prices were generated by the Dispatch model that has been used for this modeling assignment. Two different sets of electricity prices were used for this investigation. One set of historical prices from 2018, and the other set was simulated by the Dispatch model for the year 2030. Both price sets were hourly electricity prices. Resulting from the earlier mentioned buy and sell strategy, yearly revenues are determined by the tool.	• Wholesale Electricity and Natural Gas Market Data. (U.S. Energy Information Administration, 2020) • Dispatch model

The internal input values for the Tennet Storage Tool are attained from the California Energy Policy Tool.

INTERNAL INPUT

Internal input data is required to determine the project feasibility. Input allows the tool to calculate the output of the defined project size and capabilities. The following section gives an overview of the internal input values.

NAME	VALUE	SOURCE
1. CHARGE/DISCHARGE CAPACITY	The charge and discharge capacity of the battery are required to determine the maximum power input or output of the battery. This, together with the total volume of storage, determines the amount of electricity that can be bought or sold. For the modeling exercise, the charge and discharge capacity has been set at **150 MW**.	• Application research on large-scale battery energy storage system under global energy interconnection framework.(Guo, Niu, Lai, & Chen, 2018)
2. STORAGE VOLUME	The storage volume of the battery determines the maximum amount of electricity that can be stored in the battery. Three scenarios, namely **460 MWh, 1000 MWh and 2360 MWh**, are proposed based on the predictive RES curtailment situation in 2030. The 460 MWh is equal to the average amount of discarded electricity per curtailed hour. The 2360 MWh is the required capacity on average considering the continuous curtailment in a day (10 am to 4 pm in general).	• California Energy Policy tool.

For the TenneT Storage Tool, two types of assumptions were applied: user assumptions and model assumptions.

ASSUMPTIONS (1)

USER

1. CHARGE/ DISCHARGE CAPACITY

For all model runs, the charge and discharge capacity has been fixed at **150 MW**. This choice has been made to ensure that only the influence of changes in the technological characteristics and financial changes (costs, and prices.) were investigated.

2. FINANCIAL PARAMETERS

In order to ensure that the model only evaluated changes in the capital costs of battery storage, and to make sure that most of the project's specifications were equal, the only financial parameter that has been changed between 2018 and 2030 was the maximum economic lifetime. All other financial parameters were kept unchanged.

MODEL

1. PRICE-TAKER

The TenneT Storage Tool assumes that the battery storage has no market power. The storage is a price-taker. This means that the storage is assumed to have no influence on the electricity prices.

2. PERFECT FORESIGHT

The optimization of storage dispatch assumes perfect foresight of price curves which allows the unit to take maximum revenue. In reality the success rate may be lower.

For the TenneT Storage Tool, two types of assumptions were applied: User assumptions and model assumptions.

ASSUMPTIONS (2)

	USER	SOURCE
3. MARKET TYPE	The battery storage has only been evaluated for the day-ahead market. The reasoning behind this is, that the tool has been created to evaluate the Dutch electricity market. It also has two other types of short-term markets that do not completely function in the same fashion as in California.	
4. BATTERY TYPE	At the moment, Li-ion batteries are already used for large-scale electricity storage. It is said that prices of Li-ion batteries will decrease in the coming years. At the same time, the performance of this type of batteries is expected to increase. Together with the fact that Li-ion batteries are not bound to specific locations (e.g. near water for cooling), the choice has been made to only consider Li-ion batteries for this study.	• Implementation of large-scale Li-ion battery energy storage systems within the EMEA region. (Killer, M., Farrokhseresht, M., & Paterakis, N. G., 2020)

Both the internal and external inputs allowed the TenneT Storage tool to determine the project feasibility.

OUTPUT(1)

NAME	VALUES & FIGURES	INTERPRETATION

KEY RESULTS 2018

SCENARIO	460 MWH	1000 MWH	2360 MWH
Revenue per year [M$/y]	2,3	3,1	3,4
Internal rate of return [%]	-100%	-91%	-36%
Net present value [M$]	-108,2	-200,6	-447,6
Full cycles per year [#]	554	379	182
Operational lifetime [year]	8	11	15

Based on the net present values of the different scenarios in the table on the left, it can be concluded that all three project sizes with the 2018 technical and financial specifications, as well as the 2018 price series, are financially infeasible. It is clear that the revenues fall short in covering the total costs, resulting in losses upwards of 108,2 M$. Also, the lifespan of the two smallest projects is fairly short, with only 8 and 11 years respectively, considering that the construction of all projects takes 3 years. Moreover, the potential profits on investment for all sizes, indicated by the internal rate of return, are clear in the negative values. Therefore, it's advisable not to invest in large-scale battery storage just yet.

Both the internal and external inputs allowed the TenneT Storage tool to determine the project feasibility.

OUTPUT(2)

NAME	VALUES & FIGURES	INTERPRETATION

KEY RESULTS 2030

SCENARIO	460 MWH	1000 MWH	2360 MWH
Revenue per year [M$/y]	8,3	14,0	15,8
Internal rate of return [%]	4%	5%	-3%
Net present value [M$]	-11,7	-25,9	-170,4
Full cycles per year [#]	525	406	220
Operational lifetime [year]	16	20	20

From the 2030 project runs, it appears that the projects are much more feasible than the 2018 ones. Although the net present values of all three projects are still negative, the potential losses seem to be way smaller compared to the 2018 results. Furthermore, the internal rates of return are mildly positive, which indicates that there is a potential profit to be made for the investor. Also, the lifespan of the projects is longer, from which it can be concluded that more revenue can be made, with less full cycles per year. This is related to both higher prices and larger differences therein, as well as lower costs. Considering the 2030 model results, the advice to an investor would be that investments in smaller sized storage batteries could potentially be profitable, depending on the right circumstances.

A price-sensitivity analysis has been performed to identify the impact of price changes on the feasibility.

OUTPUT(3)

NAME	VALUES & FIGURES
SENSITIVITY ANALYSIS 2030 PRICES (460 MWH CASE ONLY)	

PRICES	-20%	0%	+20%	+40%	+60%	+80%	+100%
Revenue per year [M$/y]	6,6	8,3	10,0	11,6	13,3	14,9	16,6
Internal rate of return [%]	1%	4%	8%	11%	13%	16%	18%
Net present value [M$]	-22,5	-11,7	-1,2	9,2	19,5	29,9	40,3

INTERPRETATION

From the price-sensitivity analysis above, it can be concluded that changes in the prices can cause a shift in the profitability of the large-scale batteries. It is noticed that especially the change between the base-prices and +20% -prices is large in terms of the internal rate of return. That would mean that the project would potentially become a lot more profitable if the prices increase by 20% . The net present value is -1,2 M$ which is positive, considering the base values presented earlier. Needless to say that the model heavily depends on the price series and, that small changes in the prices can cause large changes in the model results. Therefore, it needs to be mentioned once more that the 2030 prices for this study have been simulated in the dispatch model on the basis of current knowledge. An attempt was made to try to model possible changes in policies, taxes and subsidies as best as possible.

The outcomes of four models provide valuable insights on the challenges to achieve the 60% RPS target by 2030

MODEL OUTPUT SUMMARY

CALIFORNIA POLICY TOOL

Energy transition roadmap to 2030 with predictive generation capacity and fuel mix· the 60% RES target is achieved in the form of 23.3% Utility Solar PV, 11.5% Onshore wind, 11.7 % distributed solar, 3.65% Geothermal and 1.93% Biomass, accompanying with the phase out of coal, nuclear and old gas plants . There is need for more policy interventions such as subsidies, carbon pricing and clean energy standard to reduce CO2 emission more radically.

DISPATCH MODEL

Renewable electricity only accounts for 52% of generation with an average 21.5% curtailment rate for Solar, Wind and Geothermal.. The average price decrease to 28.40 $/MWh by 10% compared to that in 2018, but with higher fluctuation due to the weather dependency of renewables and decreasing back-up capacity. Both power shortages and curtailment emerges with decreasing supply reliability, which indicates the necessity of electricity storage.

SYSTEM ADVISOR MODEL

The LCOE is 3.05 ¢/kWh for the onshore wind farm with 2000 MW capacity , while the offshore LCOE is at 37.52 ¢/kWh, over 10 times than onshore', due to the high CAPEX and accelerated depreciation. However, neither onshore or offshore project could recover the costs in the lifetime under the predictive price scenario. When the PPA price increases by 40% from 2.84 ¢/kWh, the NPV of the onshore project becomes positive at 234 M$ with a 11.9% IRR.

TENNET STORAGE TOOL

As for investing electricity storage, the 2030 scenario is much better than 2018 one because of more fluctuated electricity price and better technical performance like lifetime. However, three projects from 460, 1000 to 2360 MWh volume still results in the negative NPV. It seems promising that if the hourly electricity price increases by 40% , the 460 MWh project obtains a positive NPV of 9.2 M$ with a 11% IRR.

A portfolio of wind farm and storage will potentially improve the profitability than the separate investment.

INVESTMENT SUGGESTIONS

	ELECTRICITY PRICES CHANGES	-20%	0%	+20%	+40%	+60%
Onshore wind farm	Internal rate of return [%]	-2.09	2.20	3.74	11.88	19.23
	Net present value [M$]	-865.57	-499.07	-364.86	233.94	600.44
	NPV-with 20% curtailment [M$]	-649.18	-374.30	-273.64	175.45	450.33
Electricity storage	Internal rate of return [%]	1%	4%	8%	11%	13%
	Net present value [M$]	-22.5	-11.7	-1.2	9.2	19.5
Combination	Net present value [M$]	-671.68	-386.00	-274.84	184.65	469.83

COMMENTS

There is no economical feasibility to invest either the wind farm or the storage under the predictive price scenario. What's worse, the potential curtailment impose a enormous impact on the revenue of the wind farm where on average NPV decreases by around 25% . When adjusting the price, the break-even points for both wind farm and storage occur between +20% and 40% . In addition, the introduction of electricity storage will mitigate the negative impact under high price scenarios (positive NPV), and it showcases that the integrated project is more profitable and attracting compared to any single investment.

The further market design and additional policy interventions are required to incentivize the renewables investment towards the California renewable target

INSTITUTIONAL IMPLICATIONS

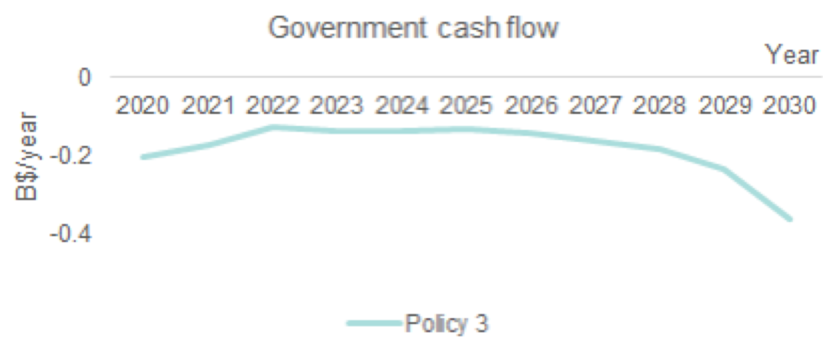
MARKET DESIGN

The demand for higher electricity price essentially indicates the demand for more revenue (sources). To deal with the low marginal cost of renewable energy, the capacity mechanism could be introduced to mitigate the private investment risk and maximize the supply reliability.

POLICY INTERVENTION

From the authority side, more subsidies or public-private partnership could be implemented to support the renewable energy and storage projects. Meanwhile, according to California Policy Model, complementary policies such as fossil fuel tax, CO2 pricing, clean energy standard are also crucial to accelerate the energy transition. For example, the CPM Policy Scenario 3 as mentioned before·, the renewable energy mix increases by 6% and CO2 emission decreases by 18% compared to BAU case at the cost of a reasonable government expenditure.

POLICY LEVERS	Δ(SCENARIO 3 - BAU)
Grid scale electricity storage	+5.50%
Onshore wind subsidy ($/MWh)	+3
Renewable energy mix	+6%
Co2 emission	-17.9%
Gov expenditure (2020-- 2030, billion $)	-1.99



TUDelft

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Thank you!