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Techno-economic Analysis of a Nuclear-Wind Hybrid System with Hydrogen Co-production

Tian Zhang

Outline

- Introduction
- Hybrid Energy System
- Modelling Approach
- Results & Discussion
- Conclusions

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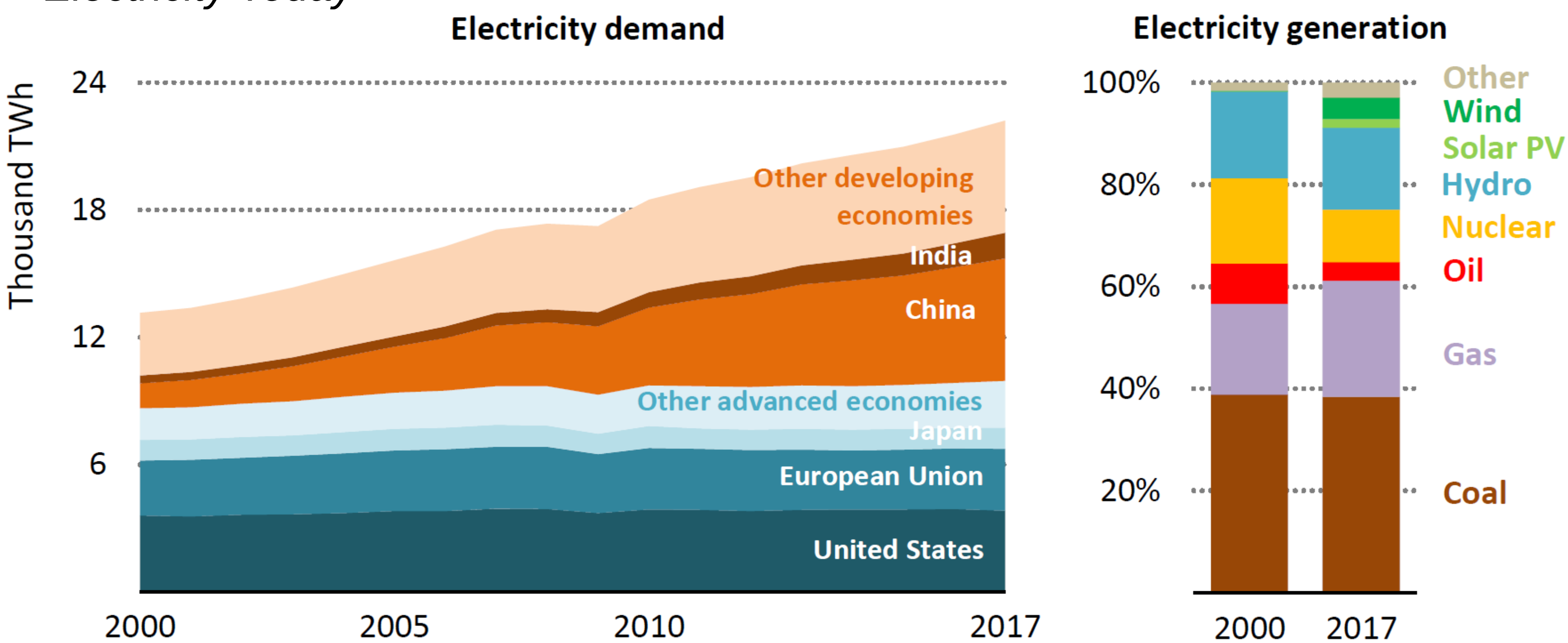
Introduction

Electricity Today

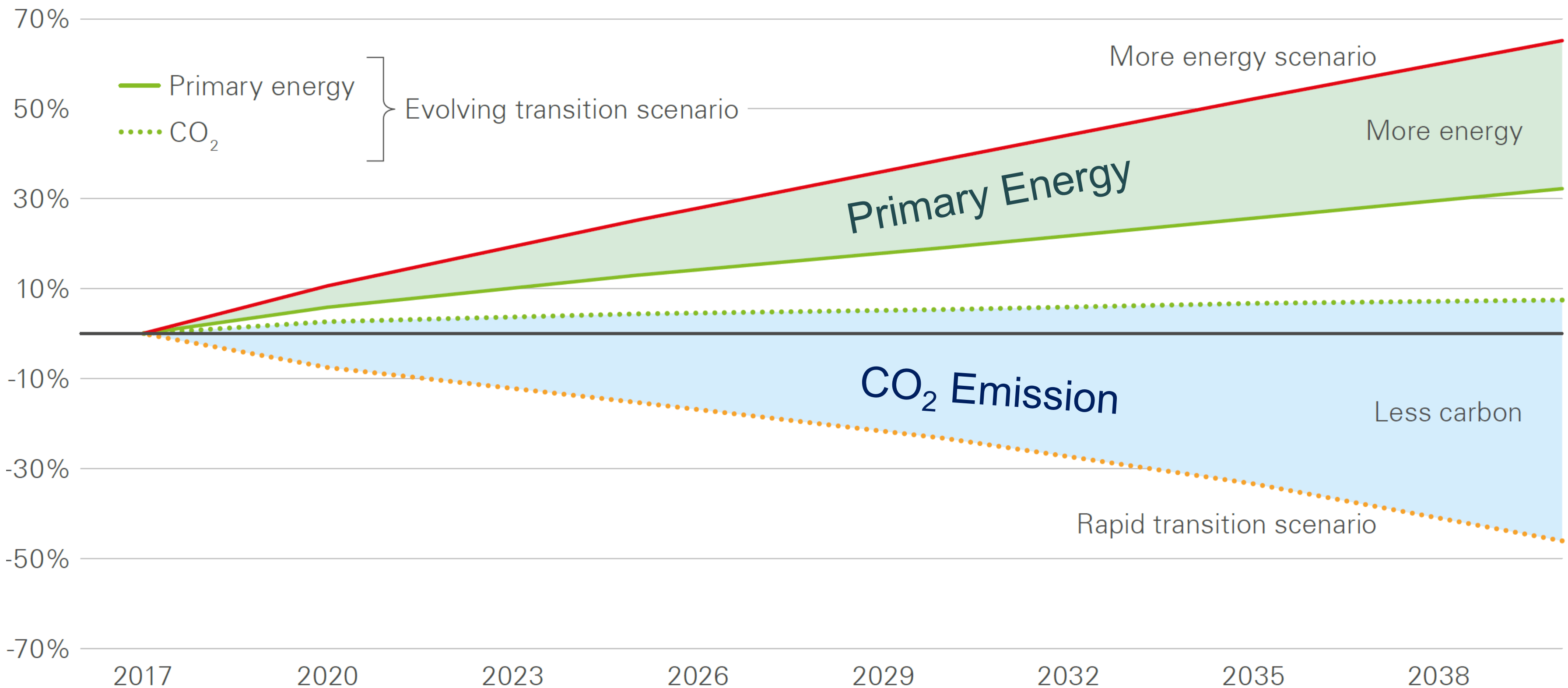


- Electricity demand kept increasing in last 20 years
- Energy mix structure has changed to have more renewables

Source: [1][2], the figure is up to year 2017, as no data is found offering same information

Introduction

More Energy and Less Carbon Emission Scenarios

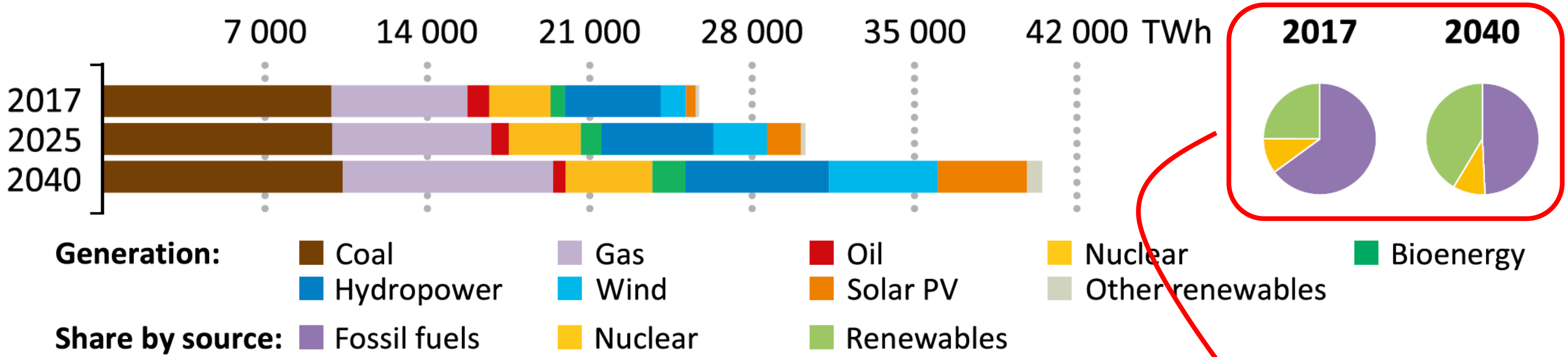


Source: [3]

Introduction

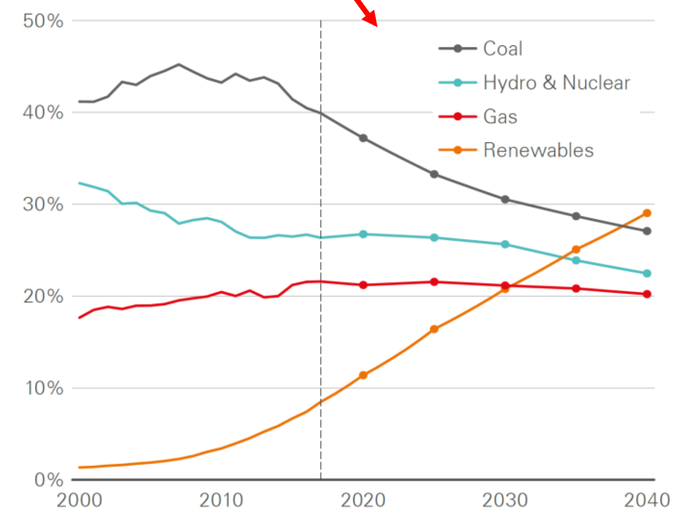
Changes of Primary Sources in Future Energy Mix

Electricity generation mix and share by source in a possible scenario



Dramatic Increment of Renewables in Future Energy Mix :

- *Reduce green house gas emission significantly*
- *Increase variability and uncertainty of the power system*

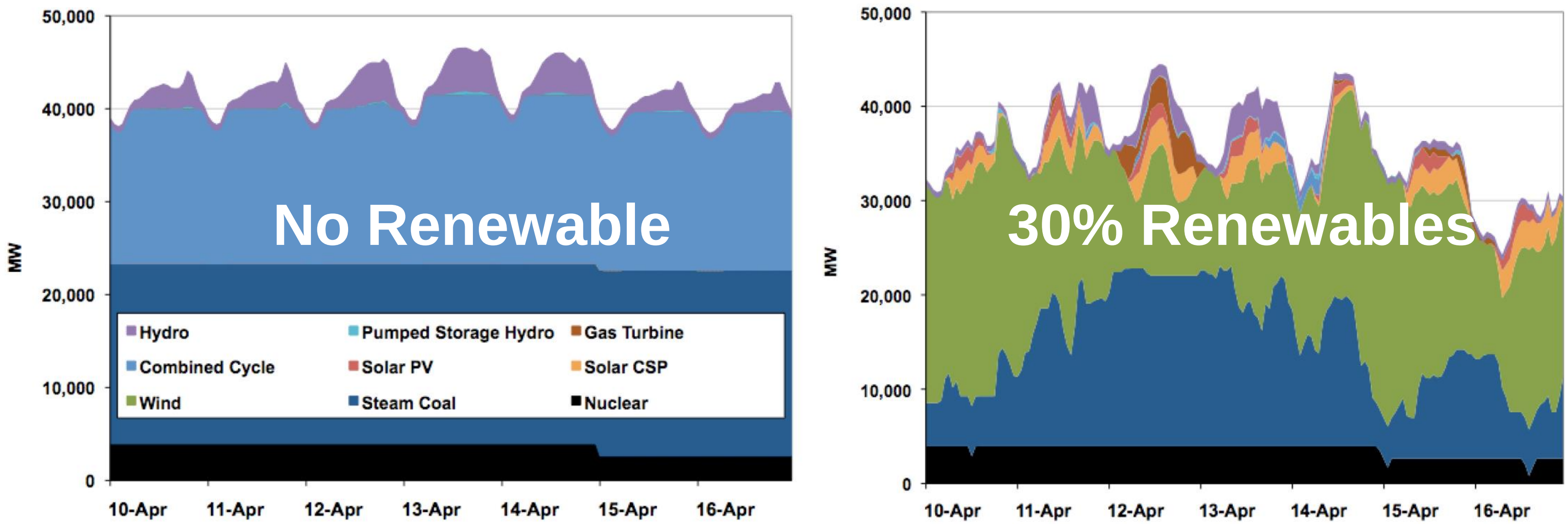


Sources: [2][3]

Introduction

Non-Dispatchable of Renewables Challenges the Grid

Grid balance in the hardest week of year 2006[4]



- More frequent occurrences of extreme electricity prices
- Reduced baseload generator market size, and associated baseload generator output reductions.

⇨ Low capital deployment efficiencies and declining of baseload technologies[5]

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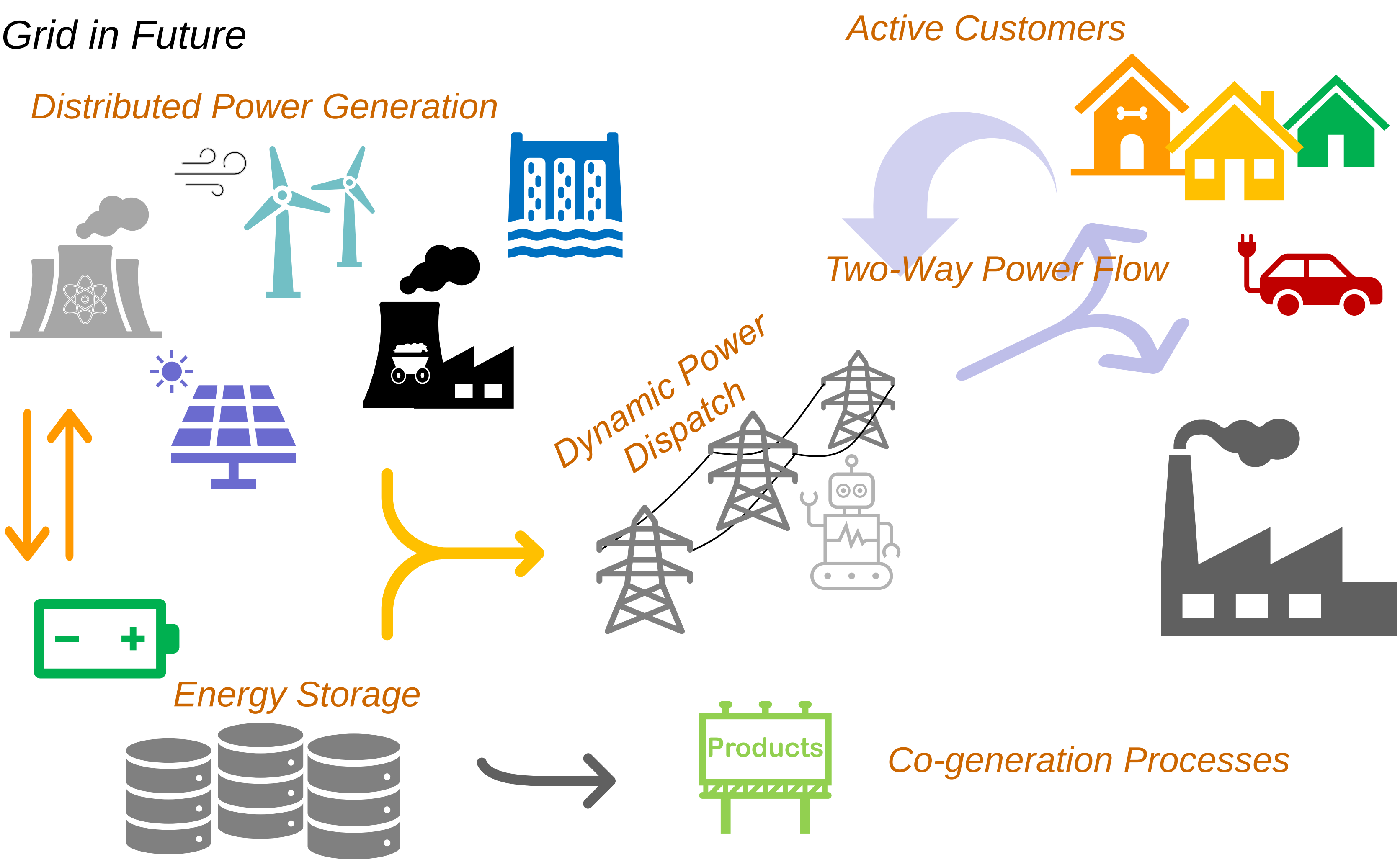
Hybrid Energy System

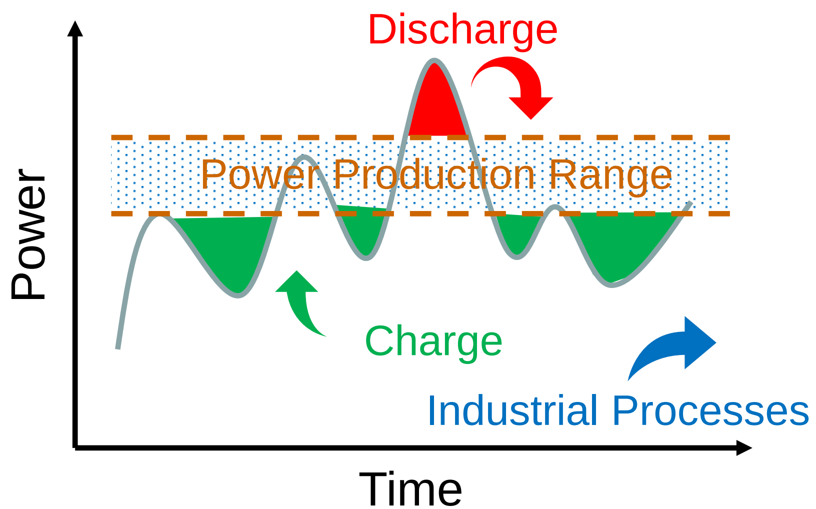
Grid in Future



Hybrid Energy System

Definition and Advantage of Hybrid Energy Systems

Hybrid Energy Systems[6]



- Combine two or more forms of energy generation, storage, or end-use technologies
- Deliver a boatload of benefits compared with single source systems

A well-designed hybrid energy system can[7]:

- Reduces greenhouse gas emission by reducing conventional power sources
- Reliable grid demand dispatch off the grid
- Economically effective with high renewable energy penetration

Hybrid Energy System

Hybrid Nuclear-Renewable System

Nuclear Energy[5]

- Sustainable, efficient and reliable, low-carbon base-load electricity source
- Large capital costs and low fuel costs require a high capacity factor
- Small Modular Reactor (SMR) designs offer flexibilities of scaling the system

Examples of Hybrid Nuclear-Renewable System[8]

Resources	Coupling Method	Storage Mode	Products
Nuclear and biomass	Thermal	Chemical	Electricity, biofuels
Nuclear and wind energy	Electrical	Hydrogen	Electricity, hydrogen
Nuclear and CSP	Thermal	Thermal	Electricity, heat
Nuclear, wind energy, and natural gas	Electrical and thermal	Chemical	Electricity, chemical products, diesel fuel

- *Will the system work as it is expected to?*
- *Does the hybrid system pay off?*

Sources: [7]

CSP: Concentrating Solar Power

Hybrid Energy System

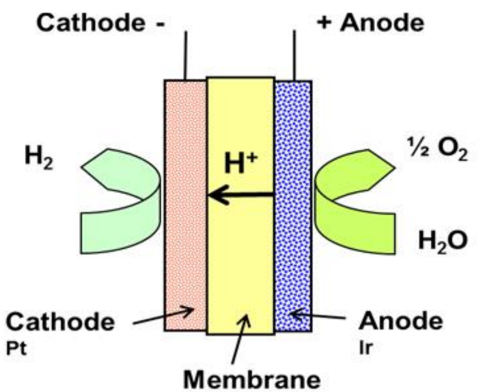
Hybrid Nuclear-Renewable System

Hydrogen Production and Electricity Conversion[9][10]

Technology	Temp. Range	Cathodic Reaction	Charge Carrier	Anodic Reaction
Alkaline electrolysis	$40-90℃$	$2H_2O+2e^- \rightarrow H_2+2OH^-$	OH^-	$2OH^- \rightarrow \frac{1}{2}O_2+H_2O+2e^-$
Membrane electrolysis	$20-100℃$	$2H^+ + 2e^- \rightarrow H_2$	H^+	$H_2O \rightarrow \frac{1}{2}O_2+2H^+ + 2e^-$
High temp. electrolysis	$700-1000℃$	$H_2O+2e^- \rightarrow H_2+O^{2-}$	O^{2-}	$O^{2-} \rightarrow \frac{1}{2}O_2+2e^-$

- Compact design
- High efficiency
- Fast response
- Easy to balance

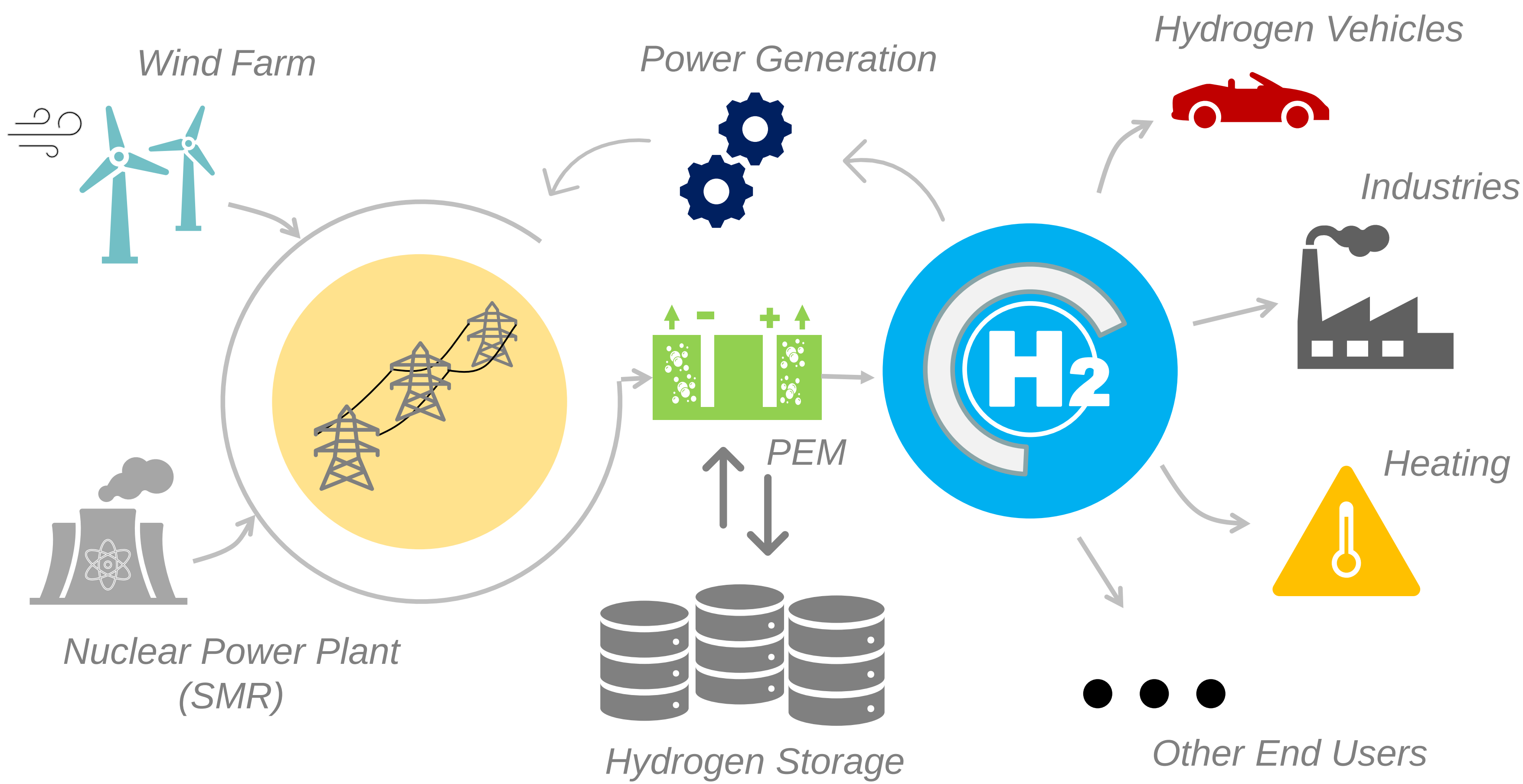
Fit to Light Water Reactor Operation Condition



Schematic of membrane electrolysis[10]

Hybrid Energy System

Hybrid Nuclear-Wind System with Hydrogen Co-production



PEM: Proton-Exchange Membrane fuel cell/electrolysis

- Introduction
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- **Modelling Approach**
- Results & Discussion
- Conclusions

- Modelling Strategy
- Code Introduction
- Technical Models
- Economic Models
- Techno-economic Coupling
- Optimization Scheme

Modelling Approach

Modelling Strategy

System Scale Optimization on Grid Demand Fitting and Economic Return

Technical

- Wind Turbine
- Nuclear Reactor
- PEM Fuel Cell/Electrolysis
- Hydrogen Storage
- Grid Data
- Energy Dispatch

Data interpolation

Deployment schedule

Economical

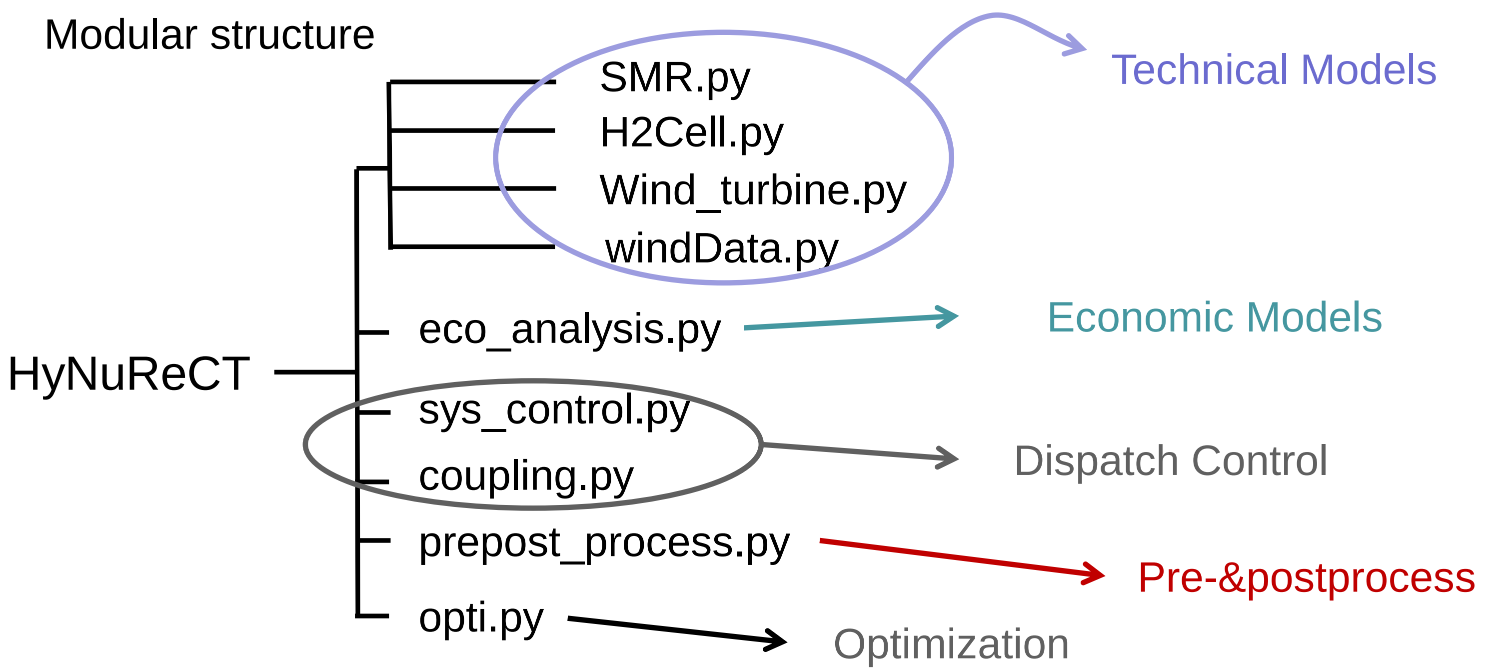
- Deployment Schedule
- Profits Estimation
- Capital and Operation Cost
- Cash Flow
- Lifetime Replacement

Modelling Approach

Code Development

HyNuReCT: Hybrid Nuclear Renewable Coupling Tools

- Self-developed code for this work in Python3
- Open source under GPLv3 license
- Accessible via github (https://github.com/tzhang0475/HyNuReCT)
- Modular structure



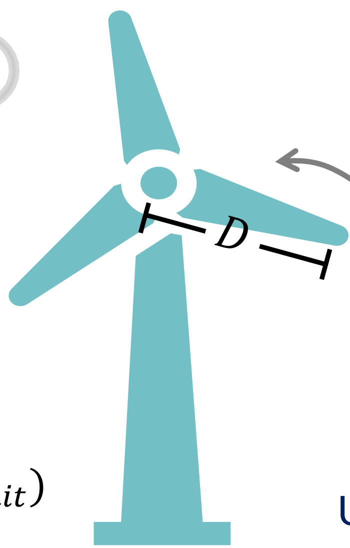
Modelling Approach

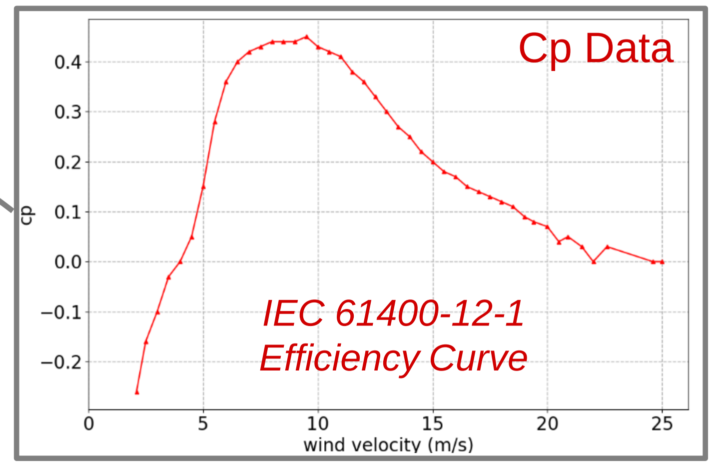
Wind Energy

Wind Farm

- Wind turbine works within user-defined cut-in and cut-out range
- Power limit P_{limit} is set by user to limit the maximum output

Wind Data





User defined curve or default IEC curve[12]

Power of Wind[11]

$$P_{wind} = \frac{1}{2}\rho_{air}\pi\left(\frac{D}{2}\right)^2 v_{wind}^3$$

$$P_{turbine} = \min(CpP_{wind}, P_{limit})$$

$$Wind\ Farm = Wind\ Turbine \times Installed\ Units$$

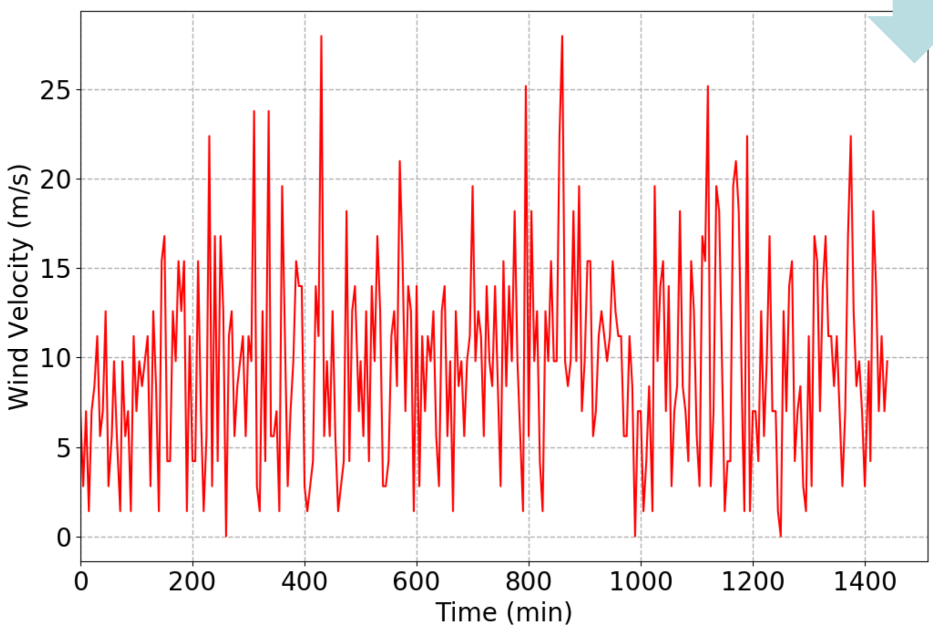
Modelling Approach

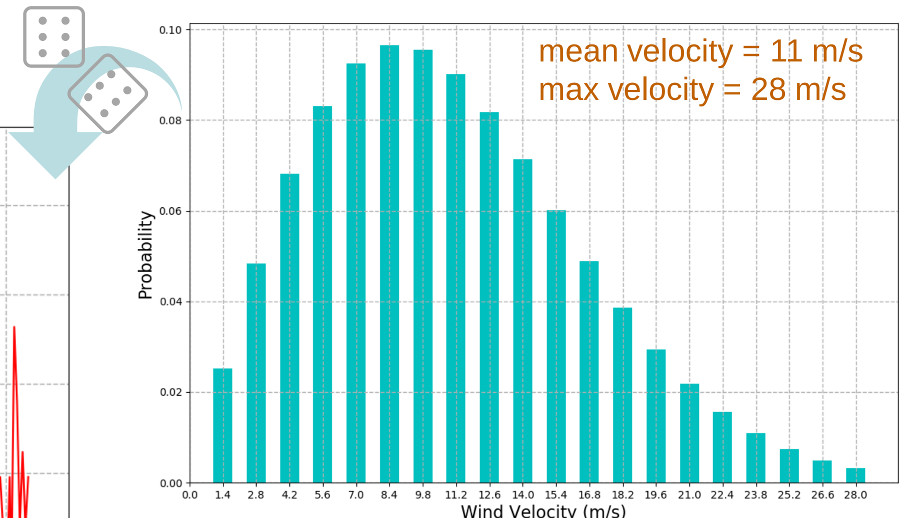
Wind Energy

Wind Data[13]

- Rayleigh probability distribution according to mean and maximum wind velocity
- Time dependent velocity generated according to probability density function
- Read from data file is also possible

Wind velocity in a day as an example





- Random number $\xi \in [0,1)$
- Wind velocity equals to cumulative probability density ξ

Modelling Approach

PEM Fuel Cell/Electrolysis

PEM Unit[14][15]

- Two-way convert between electricity and hydrogen by same mechanism
- Quasi-steady state model which assume fast response of the PEM

Faraday Constant

Convert Rate $\dot{n} = \frac{I}{2F}$

Current in PEM

$$I = \frac{P}{V_{oc}}$$

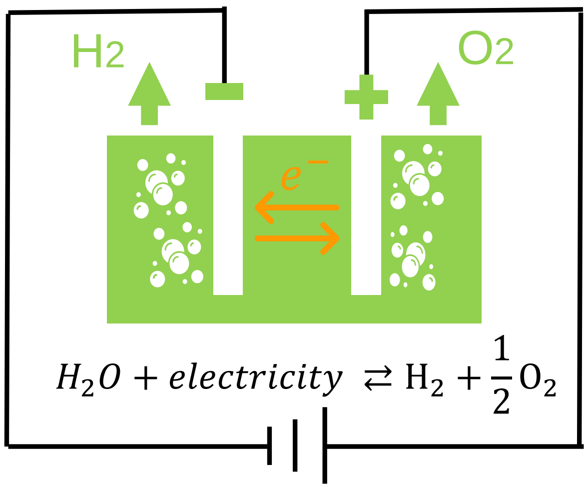
Circuit Voltage

$$V_{oc} = E_{rev} + \eta_{act} + \eta_{ohm}$$

Ohmic overpotential

Activation overvoltage

Reversible potential



$$H_2O + electricity \rightleftarrows \mathrm{H_2} + \frac{1}{2}\mathrm{O_2}$$

Reversible potential[16]

$$E_{rev} = E_{rev}^0 + \frac{RT}{2F}\log(\frac{P_{H_2}P_{O_2}}{P_{H_2O}})$$

$$E_{rev}^0 = 1.229 - 0.9 * 10^{-3} * T$$

Activation overvoltage[16]

$$\eta_{act} = \eta_{an} + \eta_{cat}$$

$$\eta_{a/c} = \frac{RT}{\alpha_{a/c}F}\sin^{-1}(\frac{I}{2i_{0,a/c}})$$

Ohmic overpotential[16]

$$\eta_{ohm} = 0.005139\lambda - 0.0326[1268(\frac{1}{303} - \frac{1}{T})]$$

Solve by Iteration

Modelling Approach

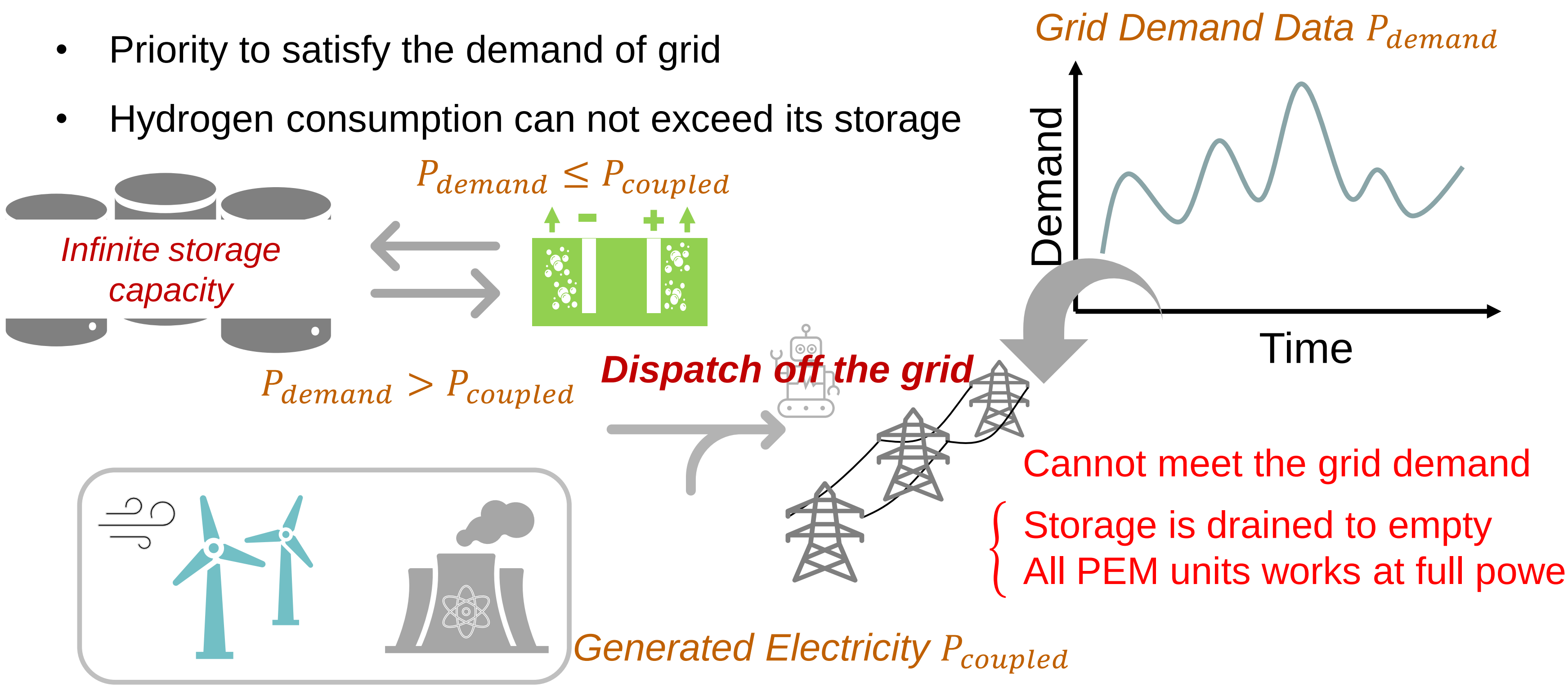
Nuclear Power Plant

Small Modular Reactor Unit

- Technically assumed to be a power generator with constant output

Power Dispatching between Grid and Hydrogen

- Priority to satisfy the demand of grid
- Hydrogen consumption can not exceed its storage



Modelling Approach

Overall Economic Evaluation[18]

Cash Flow (CF)

System Profits
- electricity to grid, hydrogen

System Costs
- cost of each component

Net Cash Flow = + Profits – Costs
+ Cash in Hands

Levelized Cost of Electricity (LCOE)

$$LCOE = \frac{Discounted\ Cost}{Discounted\ Energy}$$

in $\$/MWh$

Note: Not accurate for hybrid system

Net Present Value (NPV)

- discounted value of all annual cash flows

$$NPV = \sum_{y=0}^{n} \frac{CF_y}{(1 + r_{discount})^y}$$

NPV ≥ 0, the project make profits

Internal Rate of Return (IRR)

- the return on investment over lifetime

$$NPV = \sum_{y=0}^{n} \frac{CF_y}{(1 + IRR)^y} = 0$$

Iteration

IRR ≥ $r_{discount}$, the project make profits

Modelling Approach

Nuclear Energy Costs

Total Cost = OCC + IDC + Other Costs

Overnight Capital Cost (OCC)[19]

- Scaling of costs for different power output *(direct, indirect)*:

$$Cost = Cost_{base}\left(\frac{MWe_{new}}{MWe_{base}}\right)^{\eta}$$

inflation accounted

Default set as value suggested by OECD-NEA[22], $\eta = 0.51$ (large uncertainty)

- Combine with SMR economic features

Code of Accounts System
DOE Energy Economic Data Base[21]

- Based on typical Westinghouse four-loop plant, PWR12 (1144 MWe)
- Referred to the construction experiences during the 1970s and 1980s
- Grouped by median and better experiences data
- Values documented as 1987 dollars
- Include direct cost and indirect cost

Interests During Construction (IDC)[22]

$$IDC = \frac{N}{2}\left[\frac{OCC}{N} * (1+r)^{N-1} - \frac{OCC}{N}\right]$$

- N is number of construction year
- r is the interest rate

Other Costs[22][23]:

Utilization factor related

- Operation and maintenance (OM) cost
- Cost of reactor fuel
- Cost prepared for decommissioning (DCMS)

Modelling Approach

Nuclear Energy Costs

SMR Economic Features[23]

For SMR series of n units with output power P_e

Learning effects
- x: FOAK extra cost parameter, range 15%-55%
- y: gain in a pair of units, range 74%-85%
- z: gain in two pairs of units on the same site, 82%-95%
- k: industrial productivity coefficient, 0%-2%

Gain from co-site effects

$$f_{cosite} = \frac{1 + (n-1)(1 - F_{IND})}{n}$$

Learn from plant configuration

$$f_{lc} = \sum_{n}^{i=1} f_i \qquad f_i = \begin{cases} 1 + x \; if \; FOAK, 1 \; if \; NOAK \\ \dfrac{y/z}{(1+k)^{i-2}} \; y \; for \; i \; is \; even, z \; for \; i \; is \; odd \end{cases}$$

Learn from new technology

$$f_{lt} = (1 + \mathrm{x})\mathrm{P_e}^{-\frac{\log(1-\mathrm{R})}{\log 2}}$$

Gain from modular design simplification

$$f_{modular} = \begin{cases} 0.6, for \; P_e \leq 35 \; MWe \\ 4 * 10^{-10} P_e^3 - 10^{-6} P_e^2 + 0.0012 P_e + 0.581 \; for \; 35 < P_e < 600 \; MWe \\ 1 \; for \; P_e \geq 600 \; MWe \end{cases}$$

FOAK: First-of-A-Kind, NOAK: Nth-of-A-Kind

Modelling Approach

Comparison of nuclear cost between HyNuReCT and references[22][25][26]

Type	Power (MW) /lifetime (year)	OM ($/MWh)	Fuel ($/MWh)	DCMS ($/MWh)	Reference OCC (/kW)	Reference LCOE (/MWh)	Model OCC (/kW)	Model LCOE (/MWh)
EPR (France)	1600/60	16	9.3	0.16	$3860	$56.4	$3320	$53.3
Advanced Gen.III (USA)	1350/60	12.8	9.3	0.16	$3382	$48.7	$3609	$52.5
Nuscale (FOAK)	47.5*12/60	36.2		0.16	$5078	$65.0	$5250	$75.5
Nuscale (NOAK)	57*12/60	36.2		0.16	$3600	$65.0	$3980	$66.0

EPR and Advanced Gen. III costs are in 2009 dollar
Nuscale (FOAK) cost is in 2015 dollar
Nuscale (NOAK) cost is in 2018 dollar
Note: Power Output is changed for NuScale SMR unit as the design developed

Modelling Approach

Wind Energy and PEM Cluster Cost

- modelled by relatively simple model

Wind Energy[27]

$$Cost_{kW} * P_t * n_{units}$$

wind farm intermittence factor

Total Cost = OCC + $\boxed{\text{OM Costs + Decommissioning Costs}}$

$$Cost_{MWh} * E_{produced} = P_t * f_{inter} * time$$

PEM Cluster[28]

Total Cost = CAPEX + OPEX

$$Cost_{kW} * P_{PEM} * n_{units}$$

Defined by percentage of CAPEX

$P_{t/PEM}$ is the designed power of a wind turbine or a PEM unit

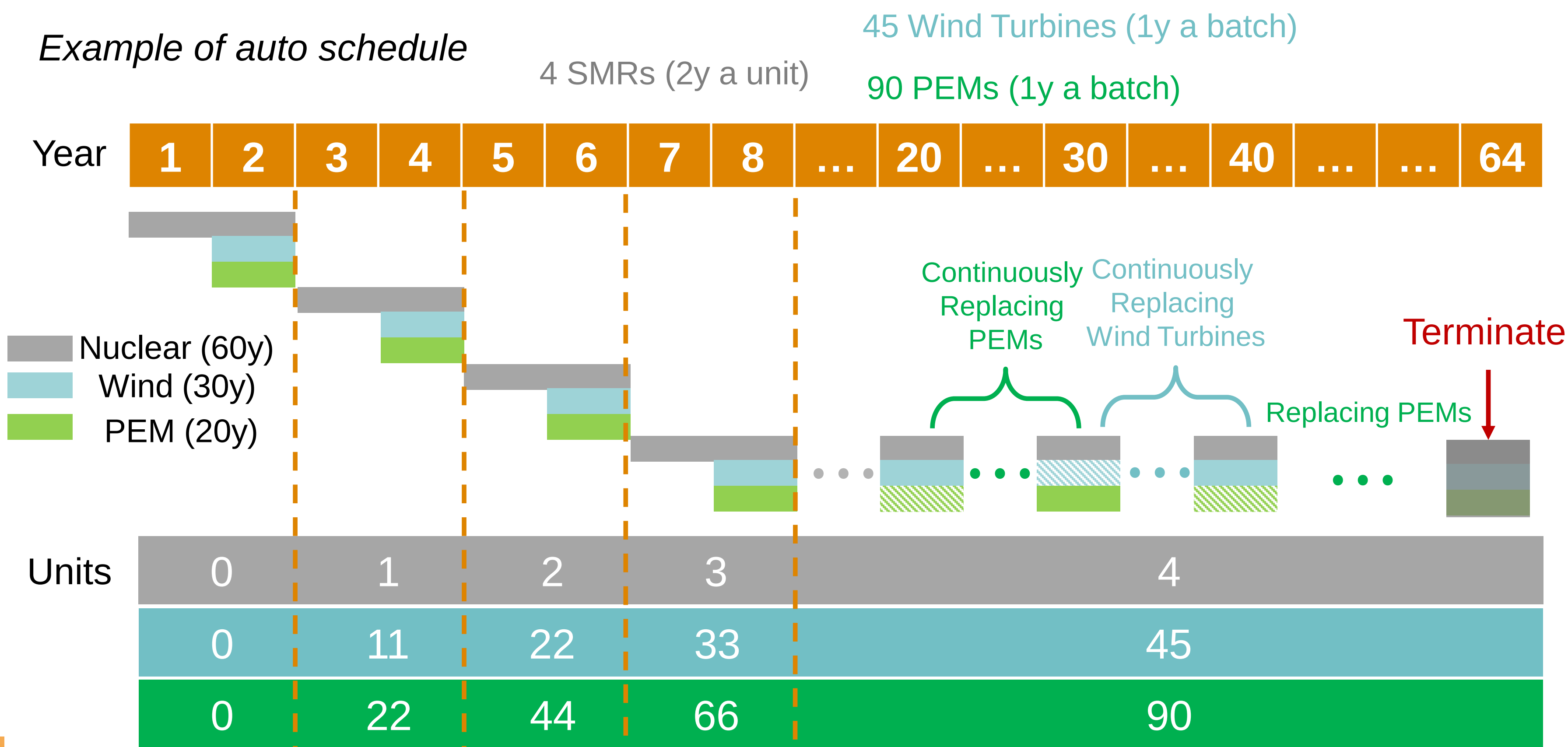
n_{units} is the number of units in a wind farm or PEM cluster

Modelling Approach

Deployment Schedule & Lifetime Replacement

- Automatic construction and replacement schedule is integrated in the model

Example of auto schedule



Modelling Approach

Techno-economic Coupling

Technical Model
- Time-dependent quasi-steady state simulation of a time period
- Generally carried out on time scale of hours, days, and months

Economical Model
- Analysis over the whole lifetime of the system
- Based on system performance of annual scale

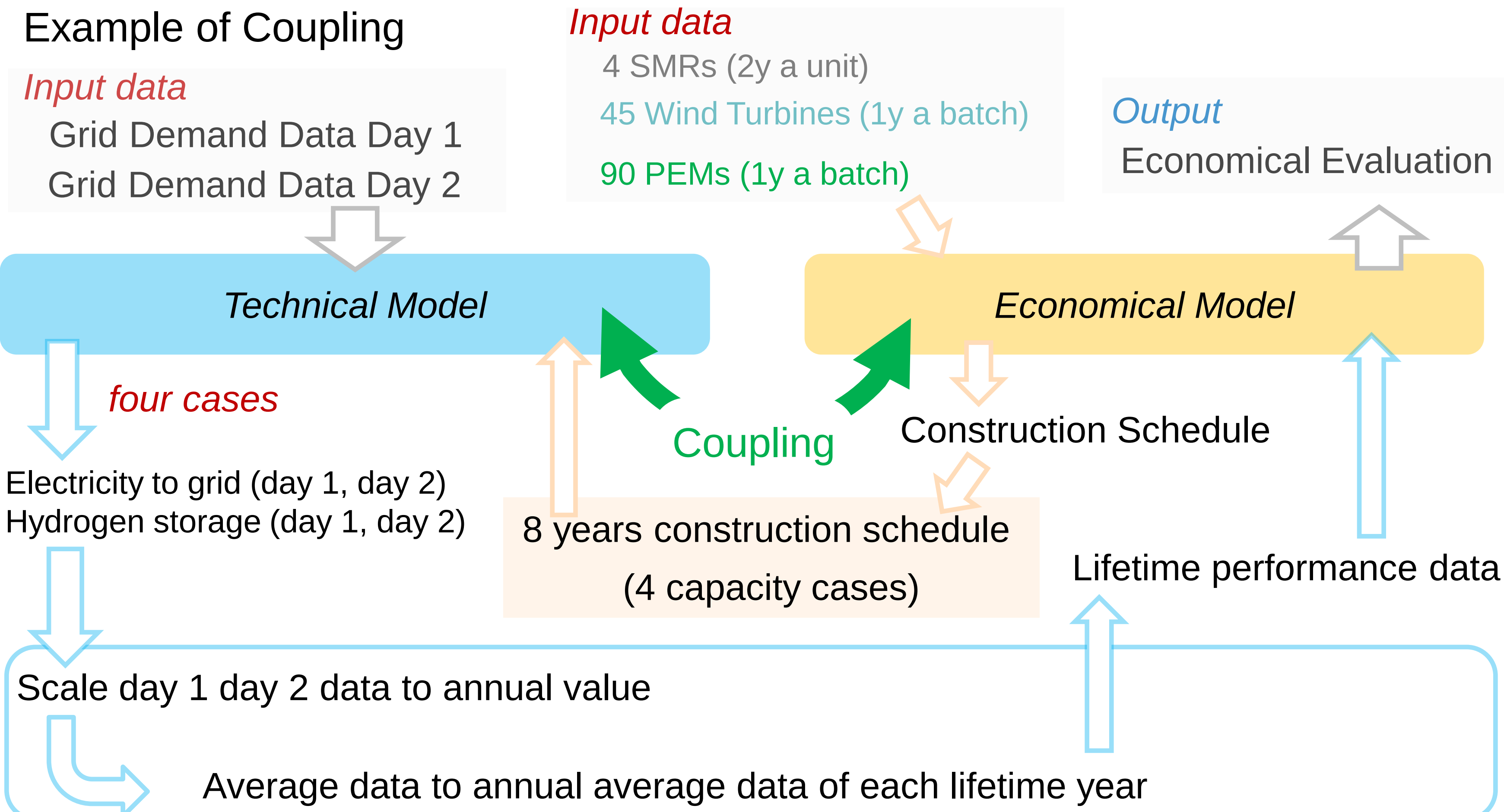
Coupling

- Calculate grid demand level during construction period
- Collect data of electricity to the grid, hydrogen stored
- Scale and average short-term data to annual value
- Adjust data according installed capacity to lifetime value
- Calculate nuclear utilization and wind intermittence factor

Modelling Approach

Techno-economic Coupling

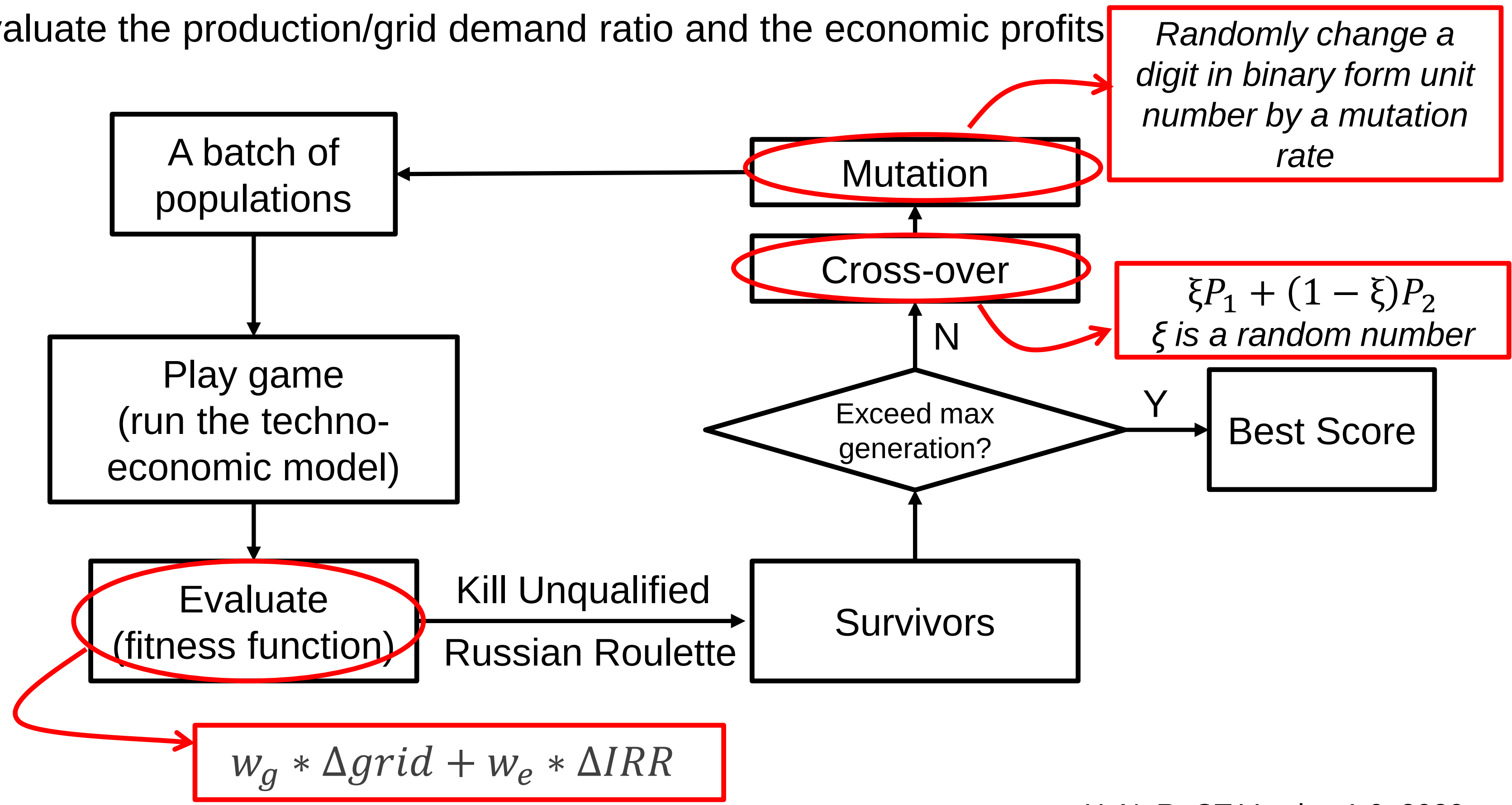
Example of Coupling



Modelling Approach

System Scale Optimization[29]

- Optimize number of units of each component in the hybrid system by Genetic Algorithm
- Evaluate the production/grid demand ratio and the economic profits



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- **Results & Discussion**
- Conclusions

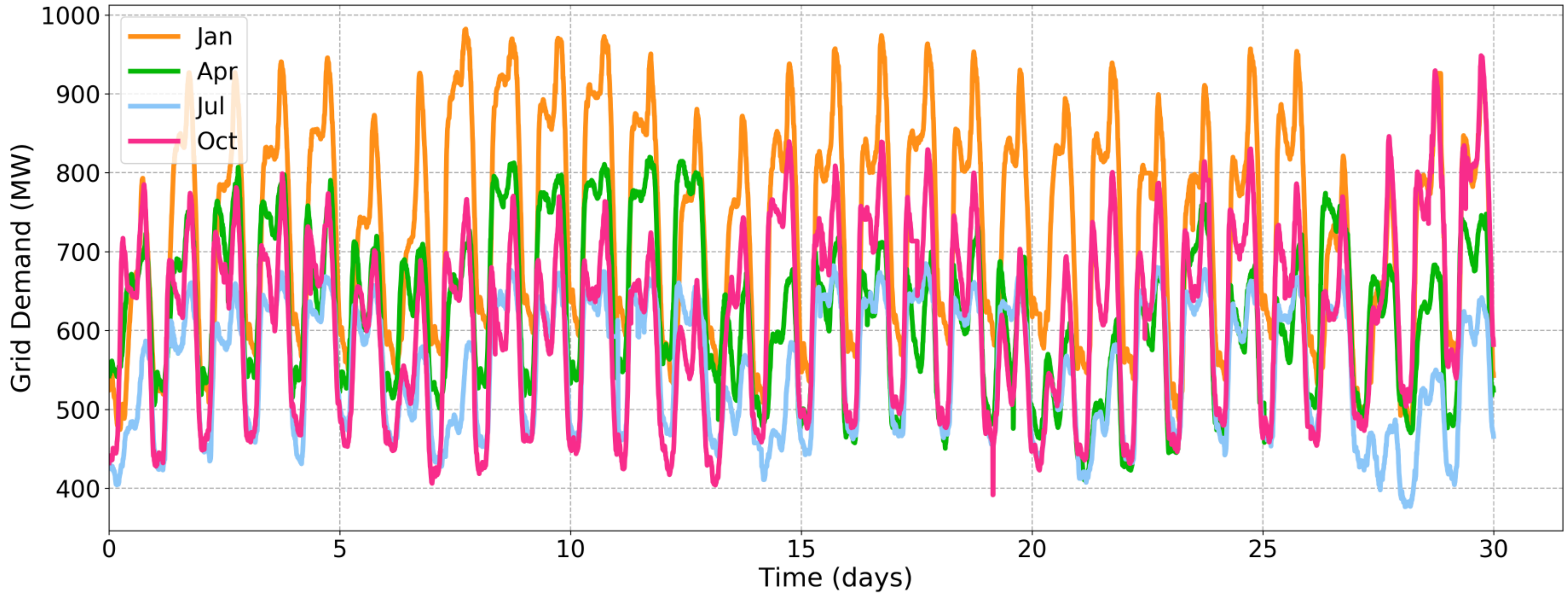
- System Parameters
- Optimization Results
- Scenarios Analyzed
- Grid Fitting Results
- Hydrogen Production Results
- Economic Evaluation

Results & Discussion

System Parameters

Grid Demand Data

- UK real grid demand in Jan., Apr., Jul., and Oct. 2018[31]
- Approx. 5 min interval between data points
- Hybrid system aiming to supply 2% of the UK grid demand



Results & Discussion

System Parameters

Unit Parameters *(Detailed parameters see appendix)*

Component	Power Designed (MW)	Power Min (MW)	Lifetime (year)	Construction time (year)
SMR Unit	100	100	60	2
Wind Turbine	2.4	0	30	1
PEM Unit	0.5	0.05 or 0	20	1

Costs Data(in $)

Nuclear Costs[22][23]		Wind Cost (land-type)[30]	
Operation Cost (MWh)	26.90	Capital Cost (kW)	1470
Fuel Cost (MWh)	9.30	Operation Cost (MWh)	12.10
Decommissioning Cost (MWh)	0.16	Decommissioning Cost (MWh)	4.00

General Economic Data[23][32]				PEM Cost [28]	
Dollar Base	2018	Discount Rate	5%	Capital Cost (kW)	1200
Electricity Price ($/MWh)			$110	Operation Cost (MWh)	2% of Capital
Hydrogen Price ($/kg)			$8		

Results & Discussion

Scale Optimization

- Optimize number of units from a rough estimate model to a techno-economical favorable model
- Performed by Genetic Algorithm
- Fitness function for evaluation is adaptable according to demand

Fitness Function

Technical *Economical*

$$w_g * \Delta grid + (10.0 - w_g) * \Delta IRR$$

$w_g = 7.0$

Target Ratio

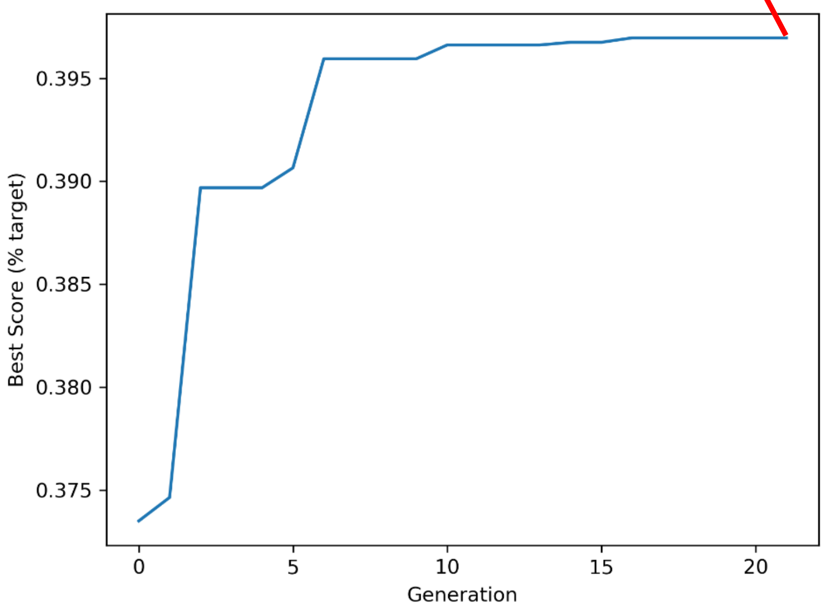
$R_{grid} - \mathbf{0.97}$

$IRR - \mathbf{r_{discount}}$

Ratio fit to grid demand

$> 0\ means\ meet\ the\ target$

Optimized Model



Results & Discussion

Scenarios Analyzed

Conservation Case

- A model with parameters target to meet the grid demands
- With and without hydrogen production and storage

Optimized Case

- A model with grid demand and economical balance optimized by Genetic Algorithm
- With and without hydrogen production and storage

Component	Number of Units	
	Conservation	Optimized
SMR Unit	6	4
Wind Turbine	150	322
PEM Unit	300 | 0	365 | 0

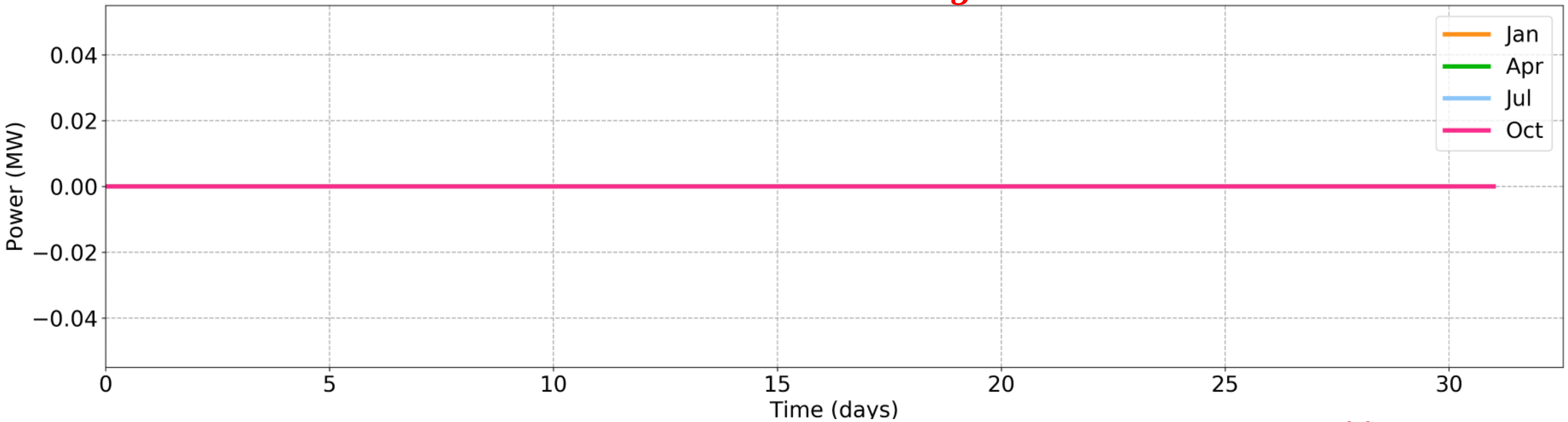
Results & Discussion

Grid Fitting Results

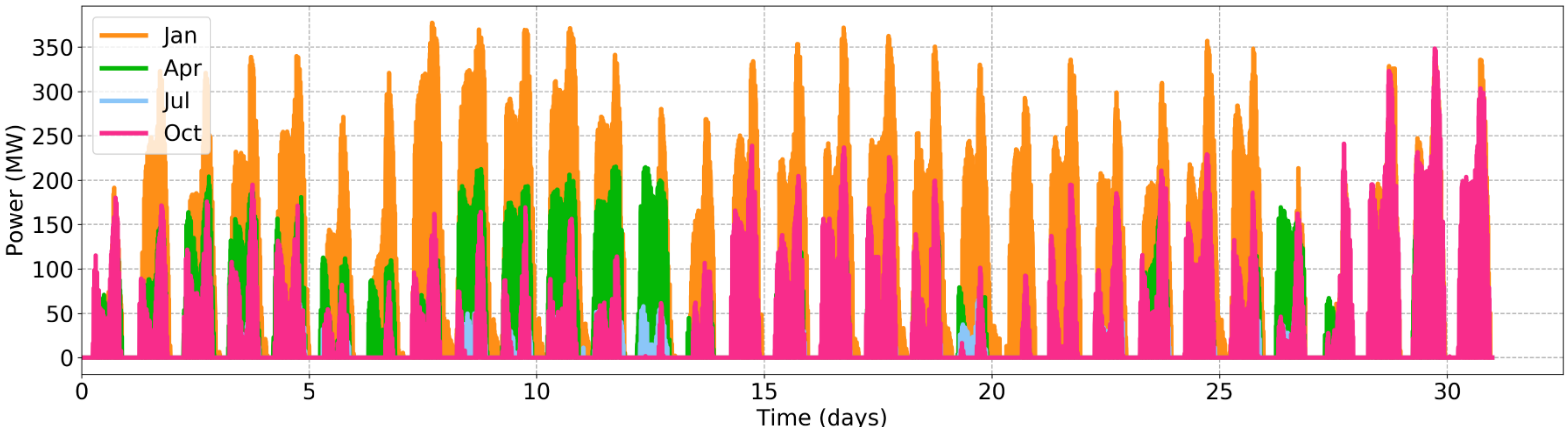
Conservation Case

$P_{demand} - P_{togrid}$

With PEMs



Without PEMs



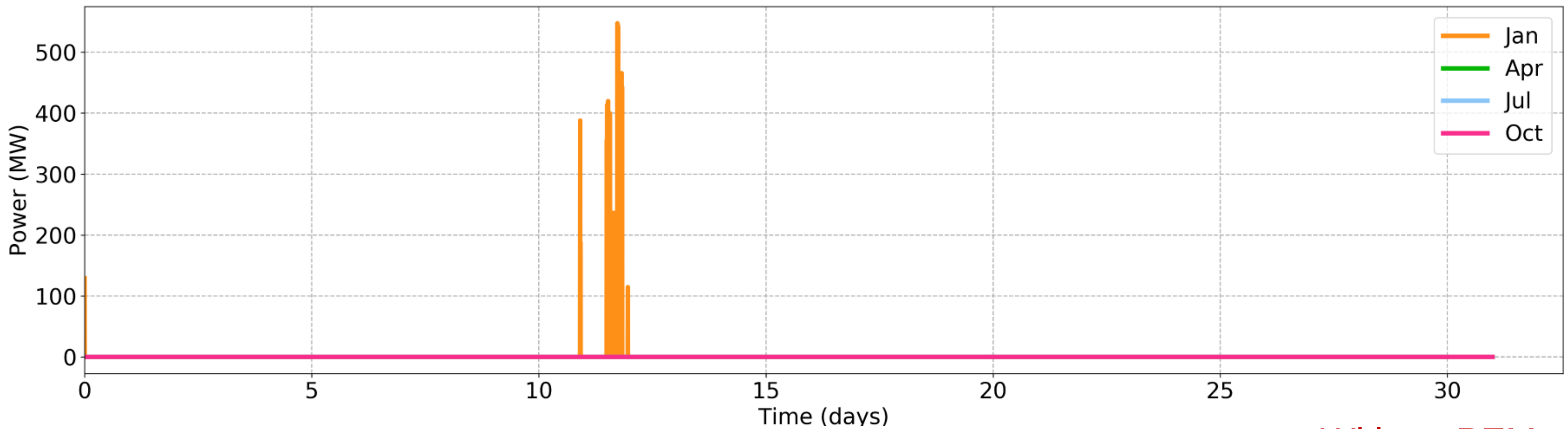
Results & Discussion

Grid Fitting Results

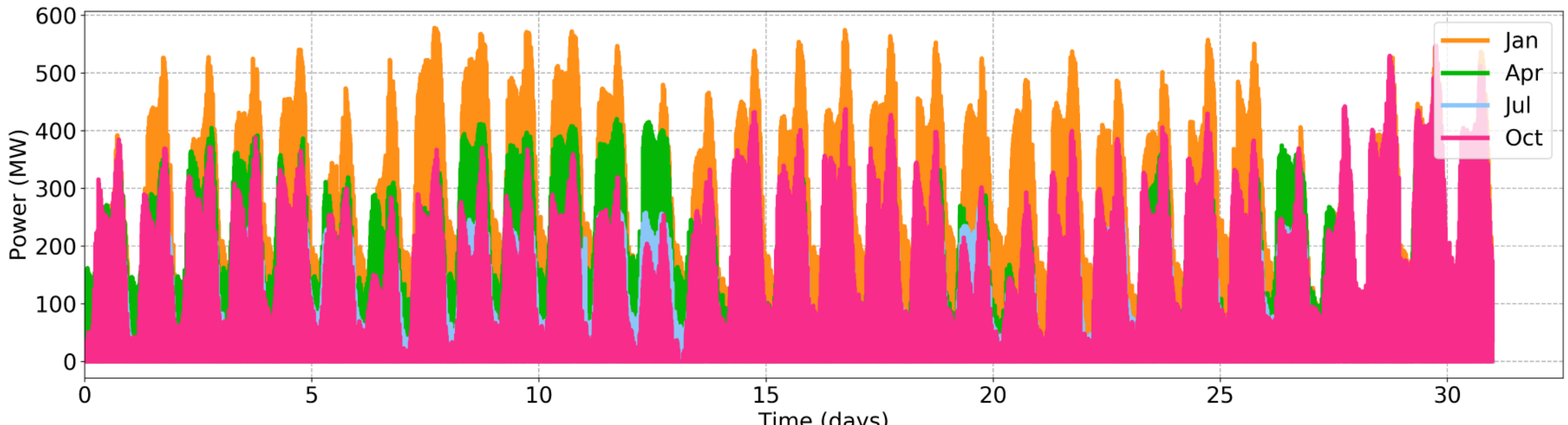
Optimized Case

$$P_{demand} - P_{togrid}$$

With PEMs

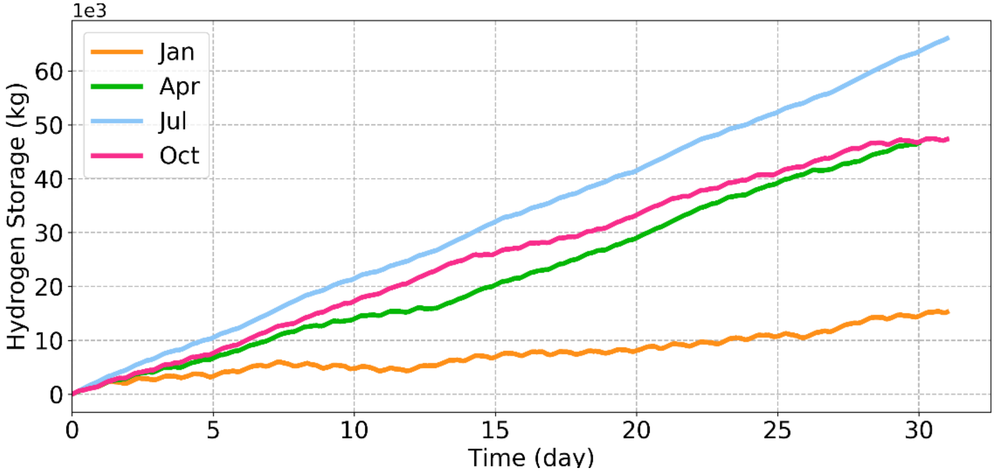


Without PEMs



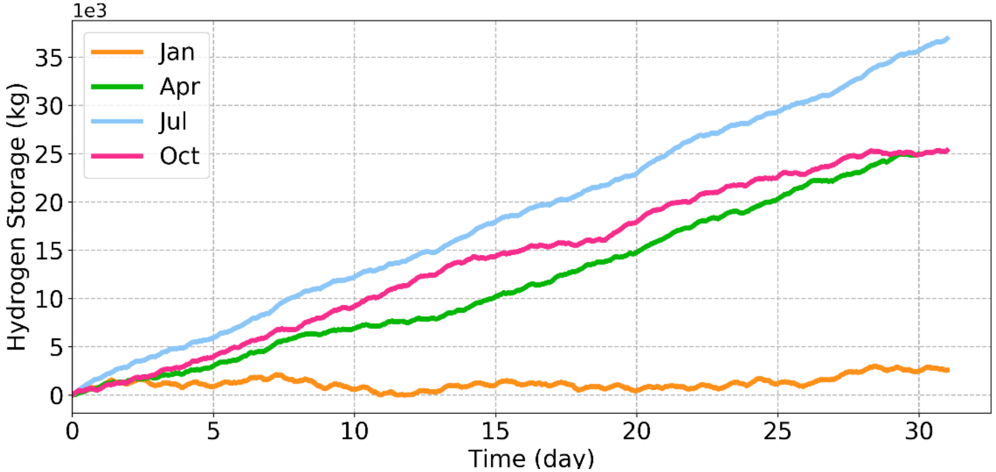
Results & Discussion

Hydrogen Production



Conservation Case

- Monthly production up to 60t by low grid demand month
- Surplus in all months

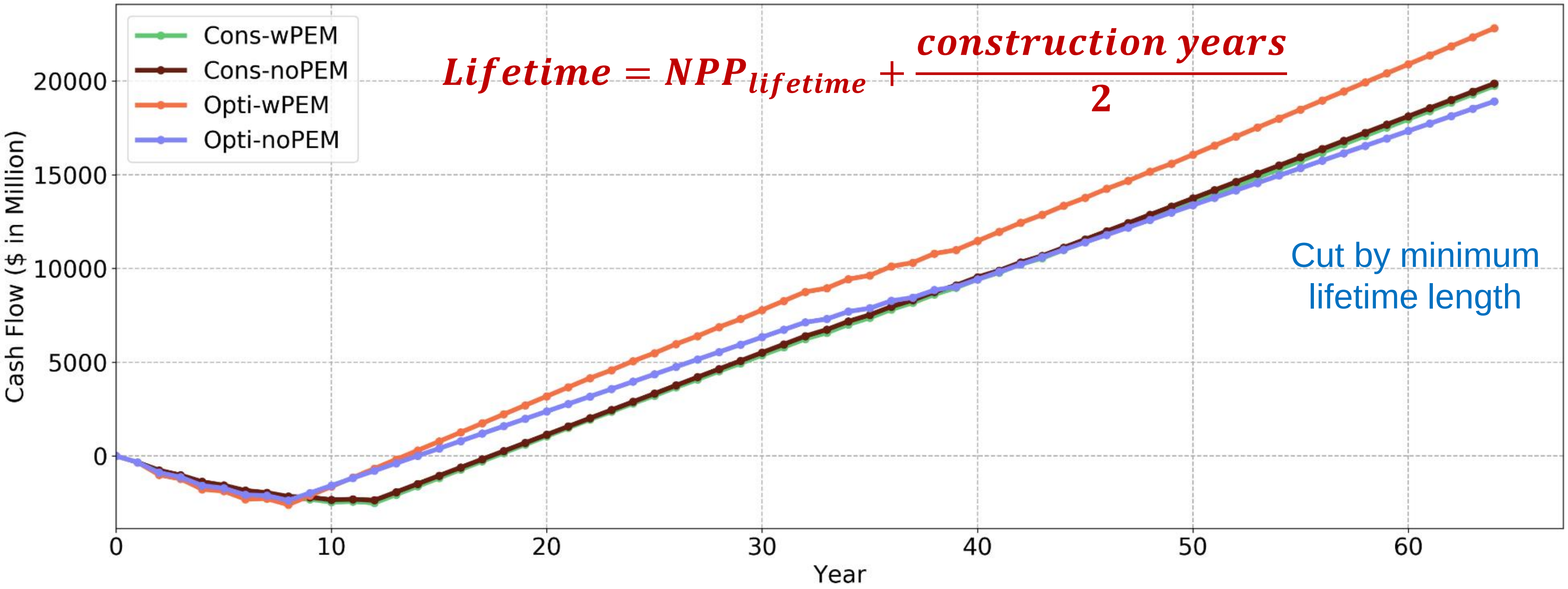


Optimized Case

- Monthly production up to 35t by low grid demand month
- Surplus in all months, in peak demand month nearly no hydrogen stored

Results & Discussion

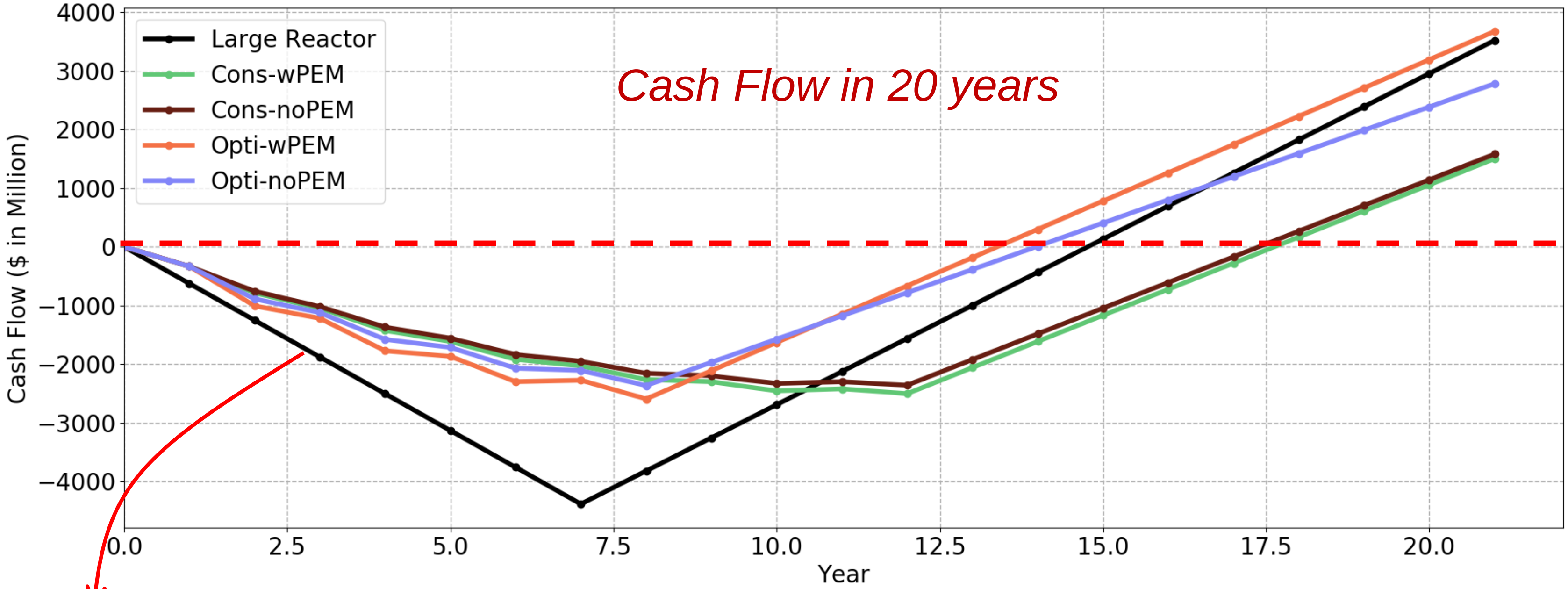
Economic Evaluation Results



Lifetime Internal Rate of Return (IRR)				
Model	Cons (wPEM)	Cons (noPEM)	Opti (wPEM)	Opti (noPEM)
IRR	8.62%	8.91%	11.20%	10.33%

Results & Discussion

Economic Evaluation Results



Reference Large Reactor

Power	1000 MW_e
Construction	7 years

Levelized Cost of Electricity (LCOE) in $				
Cons (wPEM)	Cons (noPEM)	Opti (wPEM)	Opti (noPEM)	LR
$47.37	$43.79	$40.24	$40.89	$65.63

** Hydrogen Profits are not included in LCOE*

Results & Discussion

Limitations of Current Model

- Time-independent wind mean velocity and air density
- Constant electricity price
- Quasi-steady state PEM responses
- No load following ability of nuclear power plant
- Hydrogen storage cost not yet implemented
- Hydrogen storage starts from zero for each input data
- Uncertainty and sensitivity studies not yet been performed
- Costs of dispatching and related components are not included

Electricity market will have strong impact on economic performance

⇨
- The techno-economic analysis gives the tendency of the system behavior
- The given result is accompanied with uncertainty

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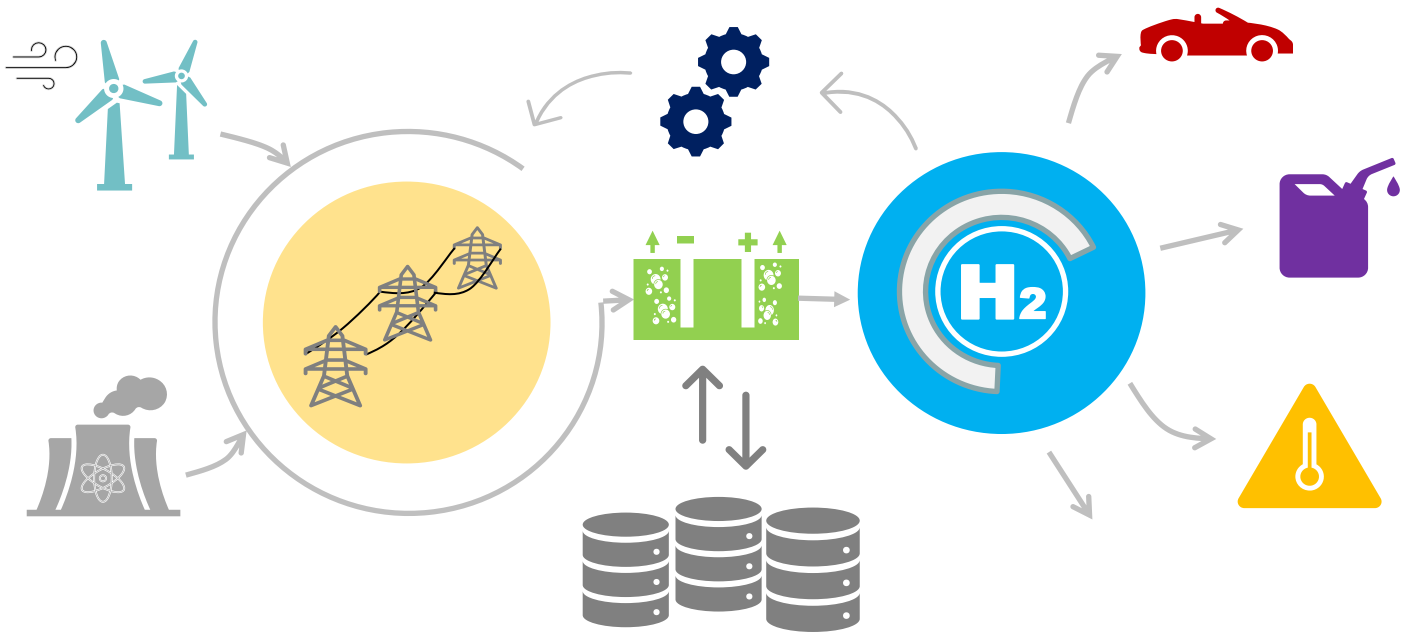
Conclusions

Hybrid Nuclear-Wind System with Hydrogen Co-production

- *Will the system work as it is expected to?*
  - The system shows its advantage on meeting the grid demand in real demand scenarios;
  - With optimization, economical performance can be improved.
- *Does the hybrid system pay off?*
  - The system shows a higher economic value in its lifetime with a more friendly cash flow and faster return rate with proper configuration;
  - Co-produced hydrogen plays crucial role in the system, in electricity market, peak power electricity may be more profitable than selling hydrogen;
  - Cost of hydrogen storage and transport influences the economic value of the system, which is not taken into account currently.

Thanks for your kind attention!



Code GitHub:

HyNuReCT: Hybrid Nuclear Renewable Coupling Tools

(https://github.com/tzhang0475/HyNuReCT)

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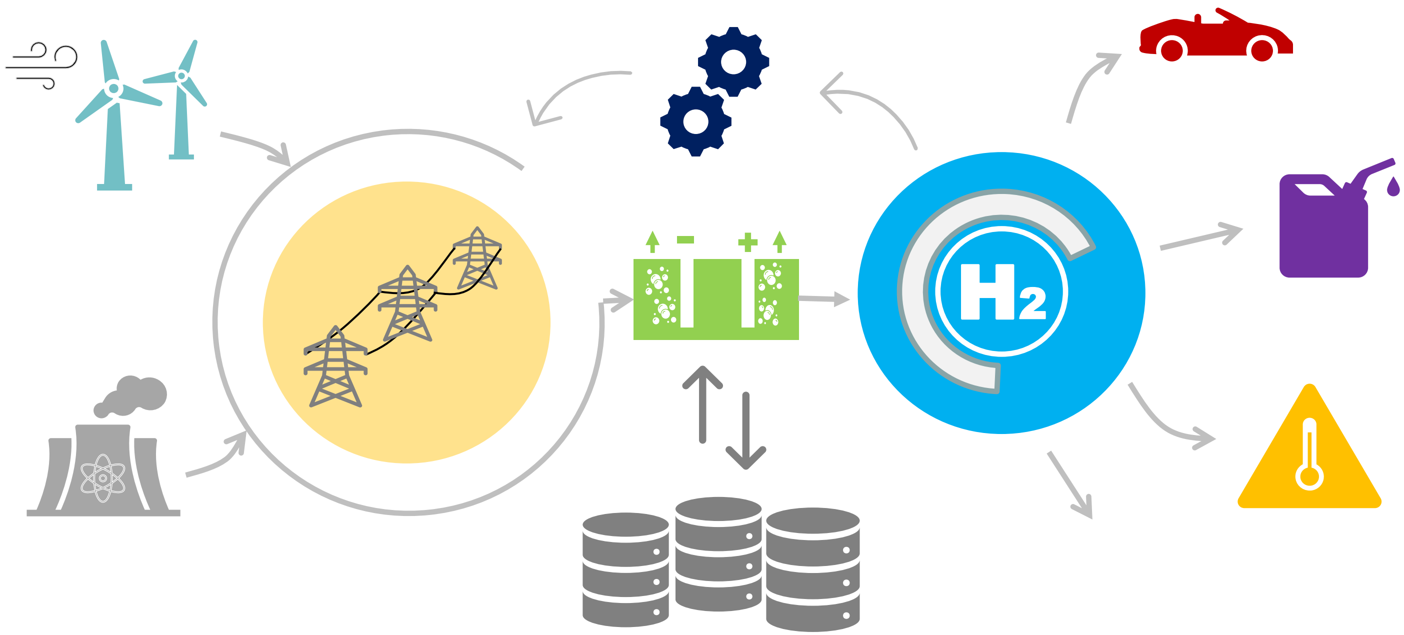
Back-up Slides



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Modelling Parameters

Wind Turbine[30]

Wing Diameter	Wind Data	Turbine Working Range	Type
90 m	Mean 11 m/s Max 28 m/s in 40 range	4.0 m/s ~ 25.0 m/s	Land Type Turbine

Nuclear Economic [22][25][26]

Scaling Factor η	x	y	z	k	Learning Rate
0.51	15%	74%	82%	2%	4%

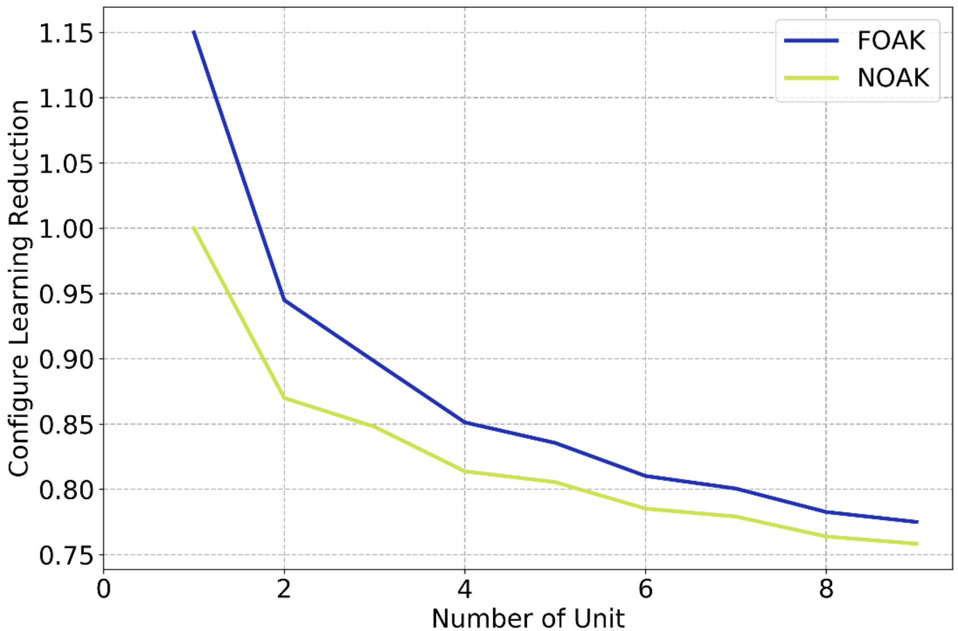
PEM Cell[9][14][15]

Operation Condition	Membrane Data	Charge Transfer Coefficient	Exchange Current Density
Temperature 80 ℃ Pressure 4 bar	Area 120 cm^2 Thickness 0.1 mm	Anode 0.5 Cathode 0.5	Anode 1e-7 A/cm^2 Cathode 1e-3 A/cm^2

SMR Economic Feature

Learn from plant configuration

$$f_{lc} = \sum_{n}^{i=1} f_i \qquad f_i = \begin{cases} 1 + x\ if\ FOAK, 1\ if\ NOAK \\ \dfrac{y/z}{(1+k)^{i-2}}\ y\ for\ i\ is\ even, z\ for\ i\ is\ odd \end{cases}$$

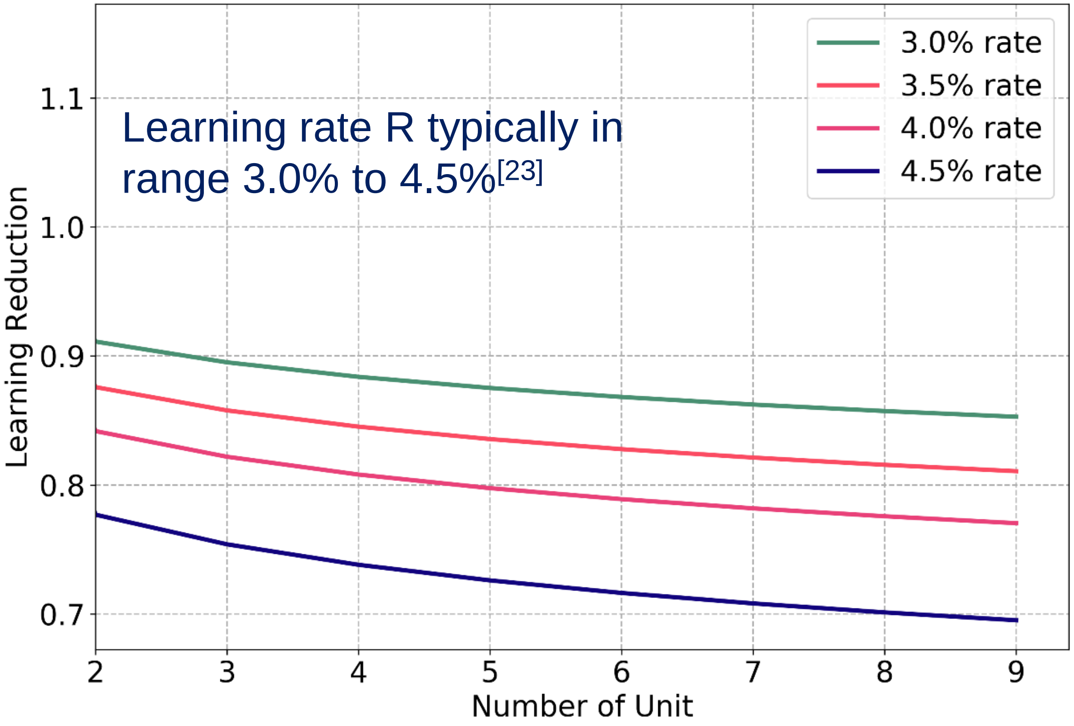


- x: FOAK extra cost parameter, range 15%-55%
- y: gain in a pair of units, range 74%-85%
- z: gain in two pairs of units on the same site, 82%-95%
- k: industrial productivity coefficient, 0%-2%

SMR Economic Feature

Learn from new technology

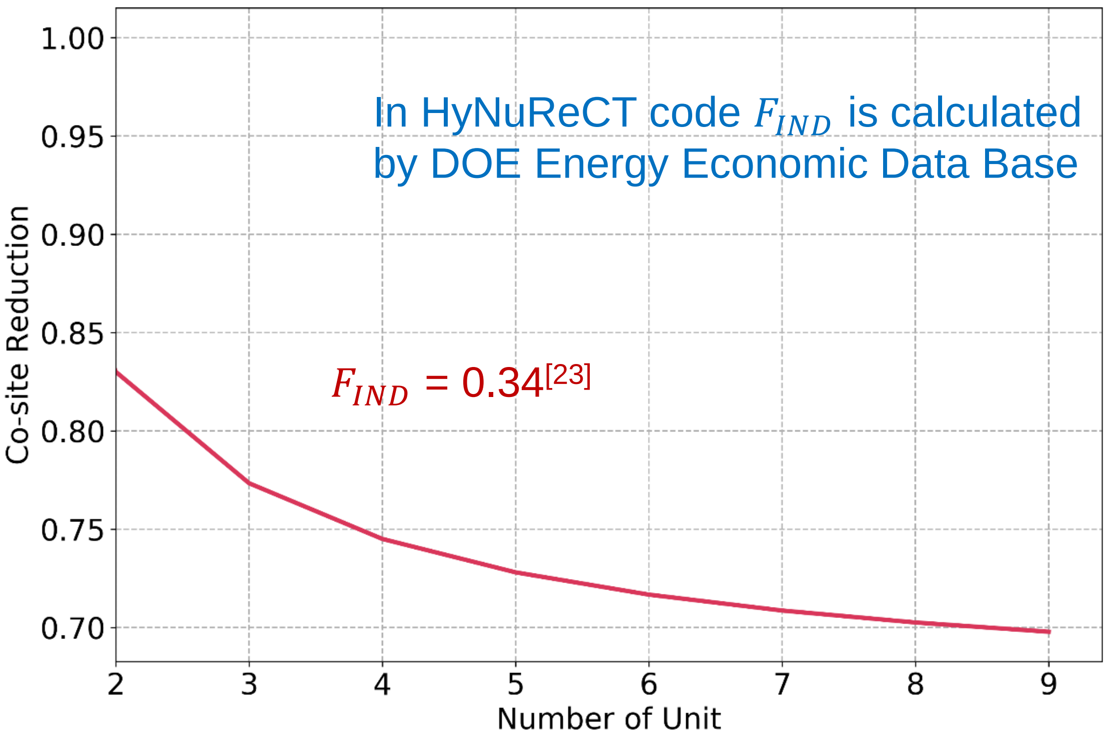
$$f_{lt} = (1 + x)P_e^{-\frac{\log(1-R)}{\log 2}}$$



SMR Economic Feature

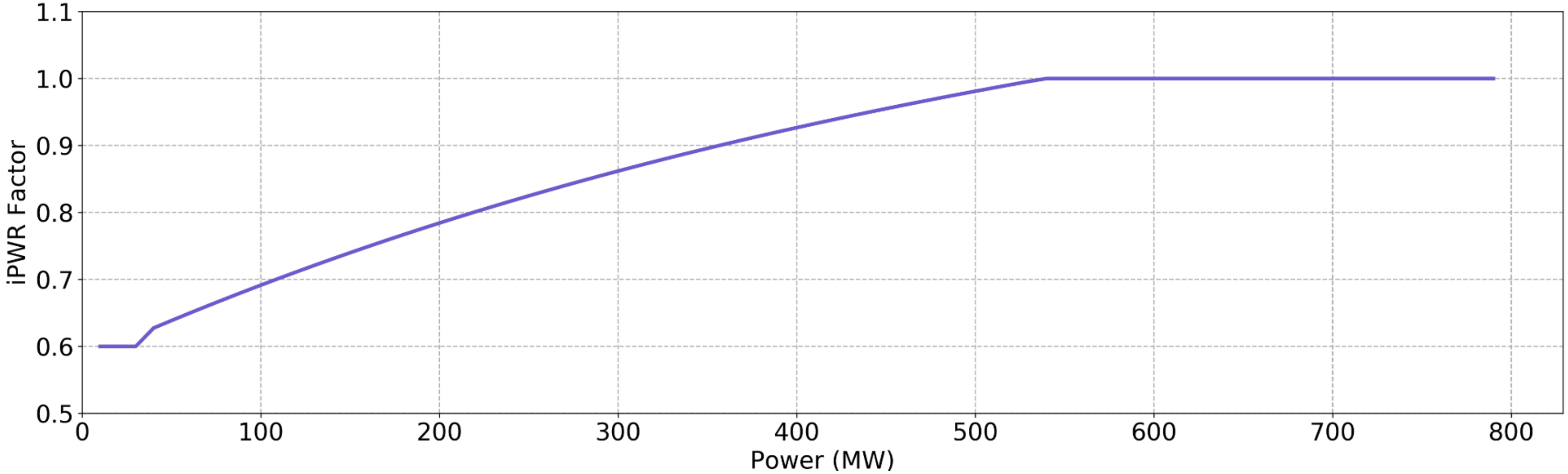
Gain from co-site effects

$$f_{cosite} = \frac{1 + (n-1)(1 - F_{IND})}{n}$$



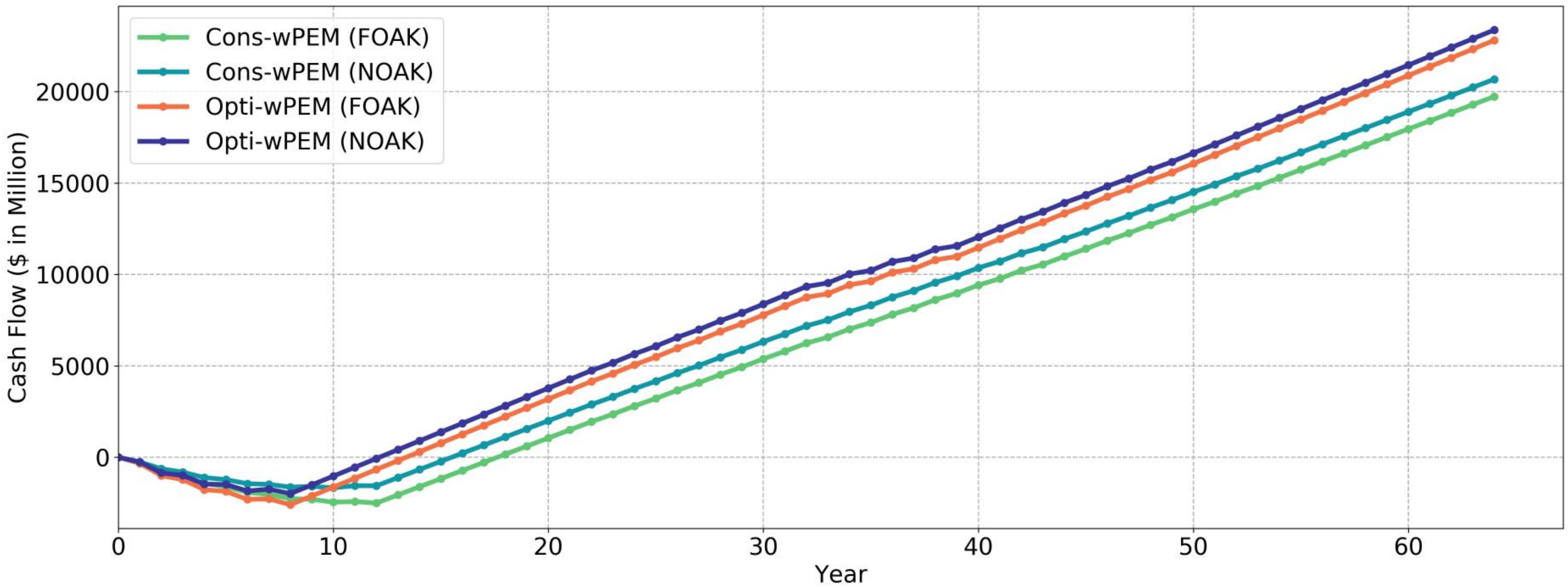
SMR Economic Feature

Gain from modular design simplification



$$f_{modular} = \begin{cases} 0.6,\ for\ P_e \leq 35\ MWe \\ 4 * 10^{-10} P_e^3 - 10^{-6} P_e^2 + 0.0012 P_e + 0.581\ for\ 35 < P_e < 600\ MWe \\ 1\ for\ P_e \geq 600\ MWe \end{cases}$$

FOAK VS NOAK



Lifetime Internal Rate of Return (IRR)				
Model	Cons (FOAK)	Cons (NOAK)	Opti (FOAK)	Opti (NOAK)
IRR	8.62%	11.00%	11.20%	13.28%