STOCHASTIC POWER GENERATION SCHEDULING USING TEMOA

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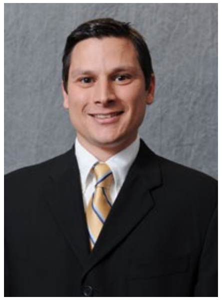
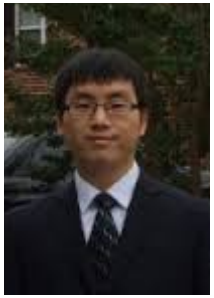


Prof. Joseph DeCarolis



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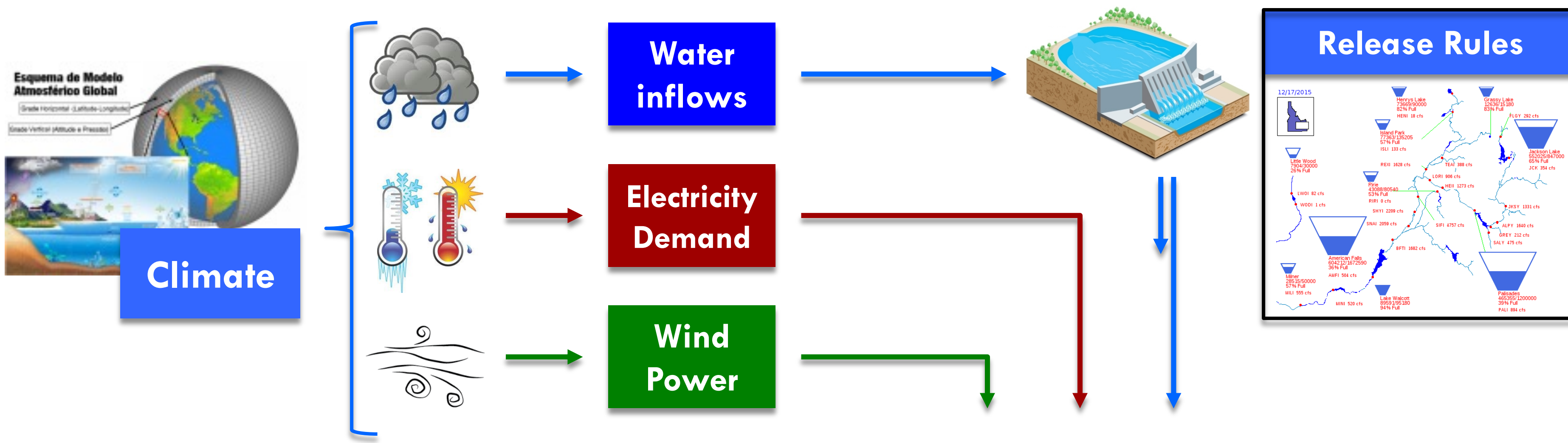
Overview

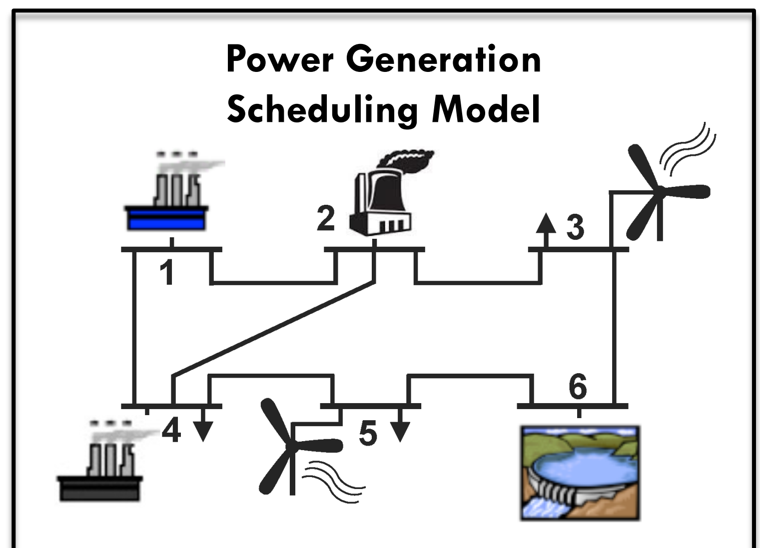
- Introduction
- Tools for Energy Model Optimization and Assessment (TEMOA)
  - TEMOA's Purposes
  - General Mathematical Formulation
- From Capacity Expansion to Power Generation Scheduling
  - Modeling Goals
  - Enhancing TEMOA Formulation
  - Stochastic Power Generation Scheduling with TEMOA
- Case Study
- Next Steps & Final Comments

Introduction

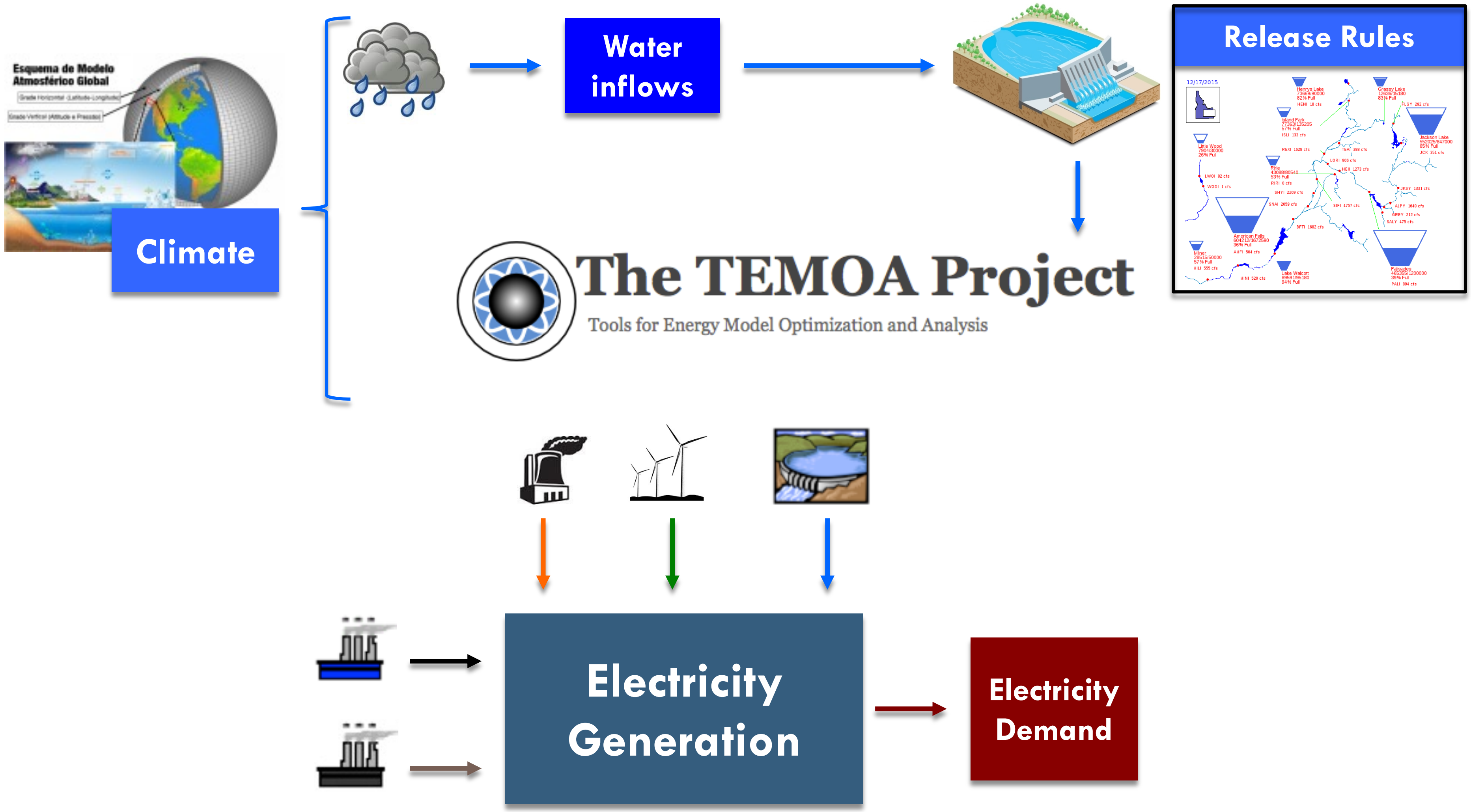
Introduction



- Multiple operational aspects
- Multi-stage problem
- Underlying uncertainties
- Complex decision process



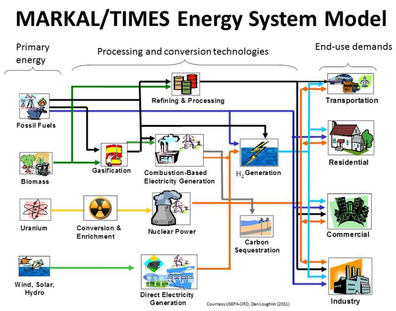
Introduction

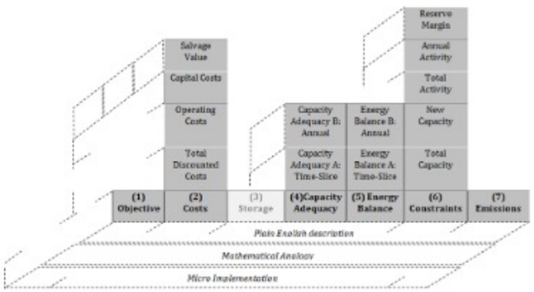


Tools for Energy Model Optimization and Assessment

Capacity Expansion Models – Energy Systems

- Models for conducting energy system analysis:
  - Markal/Times
  - OSeMOSYS
  - Message





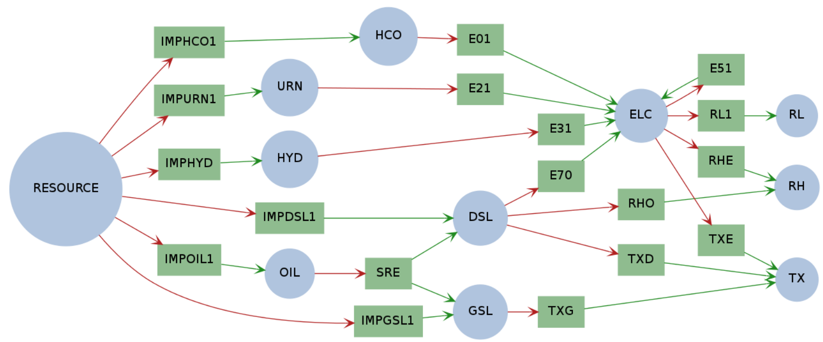
- TEMOA
  - Energy economy optimization model
  - Technology assessment and policy analysis at ≠scales
  - Model is implemented in a general algebraic formulation combined with PYOMO
  - Stochastic Programming capabilities (extensive LP and Progressive Hedging)

http://www.temoaproject.org

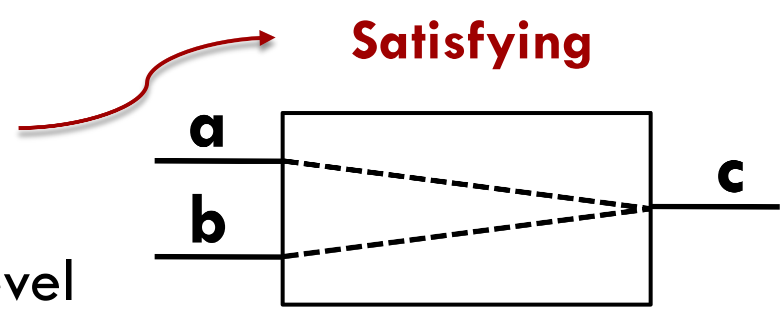
TEMOA – General Purpose

The TEMOA Project

Tools for Energy Model Optimization and Analysis



- TEMOA represents a capacity expansion and operational model for energy systems
- Represents a multi-stage problem in a network with multiple technologies and multi-commodities
- **Model's objective:** minimize cost of energy supply over a defined time horizon (present + expected future cost)
- Processes represented in a macro level



Commodity flow balance

TEMOA Mathematical Formulation

$$\text{LoanCost} = \sum_{t,v}\left(\left[IC_{t,v} \cdot LA_{t,v} \cdot \sum_{y=0}^{MLL_{t,v}} \frac{1}{(1+GDR)^{y+v-P_0}}\right] \cdot \mathbf{CAP}_{t,v}\right)$$

$$\text{FixedCost} = \sum_{p,t,v}\left(\left[FC_{p,t,v} \cdot \sum_{y=0}^{MTL_{p,t,v}} \frac{1}{(1+GDR)^{y+p-P_0}}\right] \cdot \mathbf{CAP}_{t,v}\right)$$

$$\text{VariableCost} = \sum_{p,s,d,t,v}\left(\left[VC_{p,t,v} \cdot \sum_{y=0}^{LEN_p} \frac{1}{(1+GDR)^{y+p-P_0}}\right] \cdot \mathbf{ACT}_{p,s,d,t,v}\right)$$

$$\min_{\substack{\text{ACT,FI,FO}\\\text{CAP,CAPVAL}}} \quad \textbf{Total Cost = LoanCost + FixedCost + VariableCost}$$

s.t.

$$\mathbf{ACT}_{p,s,d,t,v} = \sum_{i,o} \mathbf{FO}_{p,s,d,i,t,v,o} \quad \forall\{p,s,d,t,v\} \in \Theta_{\text{activity}}$$

Process activity

$$\left(CF_{s,d,t,v} \cdot C2A_t \cdot SEG_{s,d} \cdot TLF_{p,t,v}\right) \cdot \mathbf{CAP}_{t,v} \geq \mathbf{ACT}_{p,s,d,t,v} \quad \forall\{p,s,d,t,v\} \in \Theta_{\text{activity}}$$

Technology capacity

$$\sum_{i,t,v} \mathbf{FO}_{p,s,d,i,t,v,c} \geq DEM_{p,c} \cdot DSD_{s,d,c} \quad \forall\left\{p,s,d,c \in C^d\right\} \in \Theta_{\text{demand}}$$

Supply-demand

$$\mathbf{FO}_{p,s,d,i,t,v,o} \leq EFF_{i,t,v,o} \cdot \mathbf{FI}_{p,s,d,i,t,v,o} \quad \forall\{p,s,d,i,t \in T - T^s, v, o\} \in \Theta_{\text{flow}}$$

Process-level commodity flow

$$\sum_{i,t,v} \mathbf{FO}_{p,s,d,i,t,v,\mathbf{c}} \geq \sum_{t,v,o} \mathbf{FI}_{p,s,d,\mathbf{c},t,v,o} \quad \forall\{p,s,d,c\} \in \Theta_{\text{balance}}$$

Global commodity balance

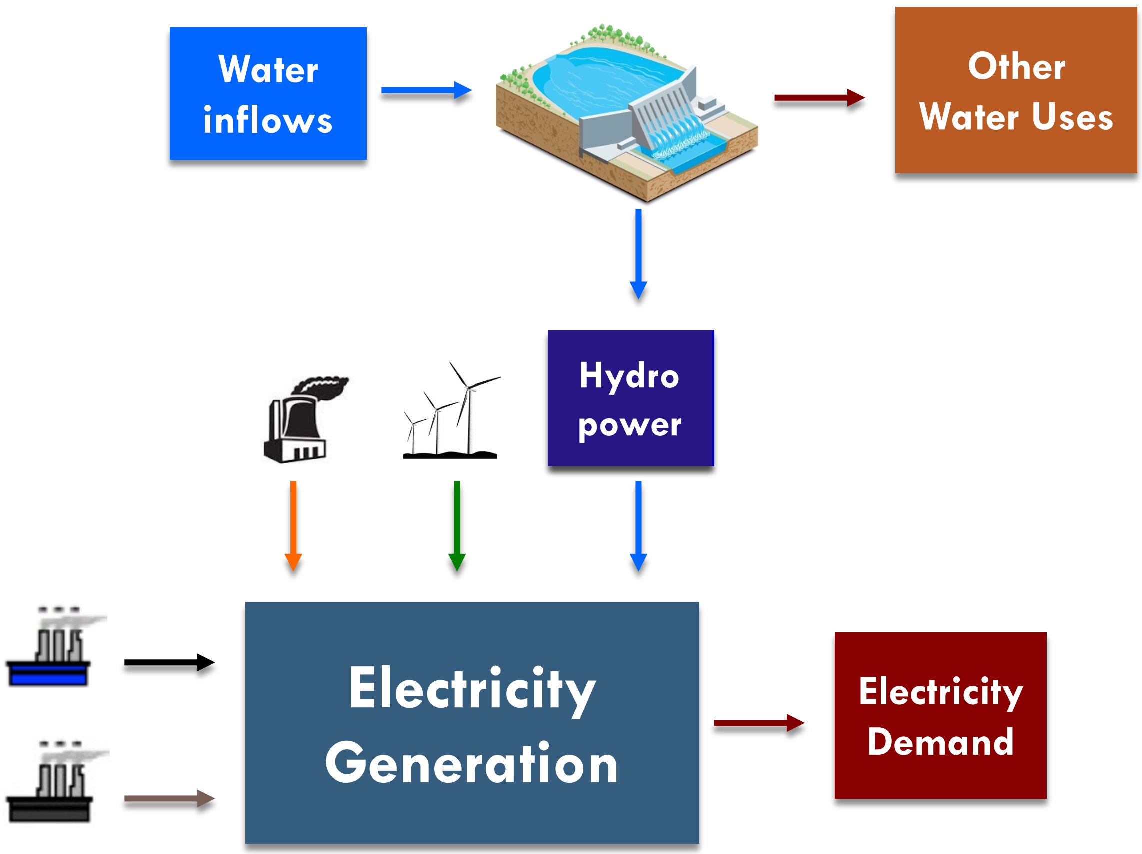
Other constraints and bounds: baseload, emissions, battery storage,…

From Capacity Expansion to Power Generation Scheduling

Modeling Goals

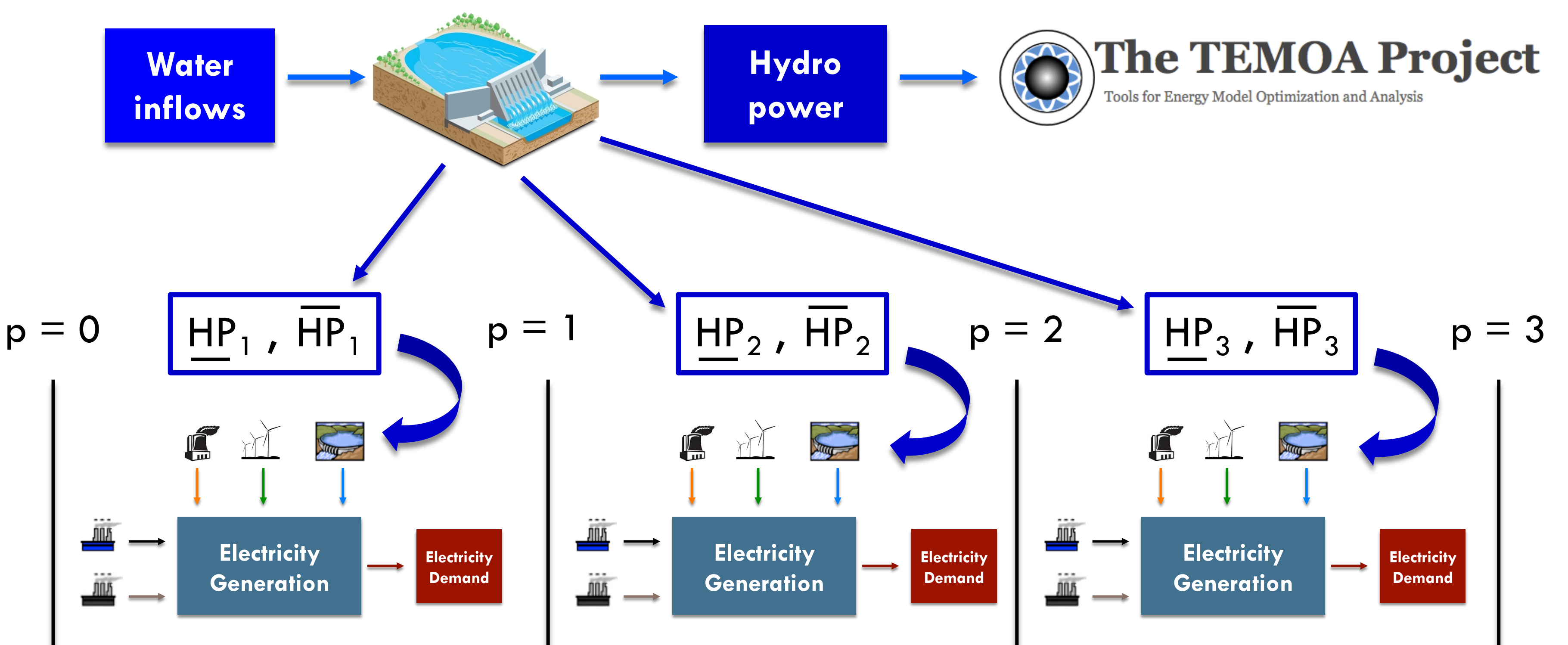
- Represent a short-term problem with monthly discretization for time periods
- Improve the representation of the system dynamics
- Include randomness in terms of resource availability at each time period

Modeling Goals *(cont.)*



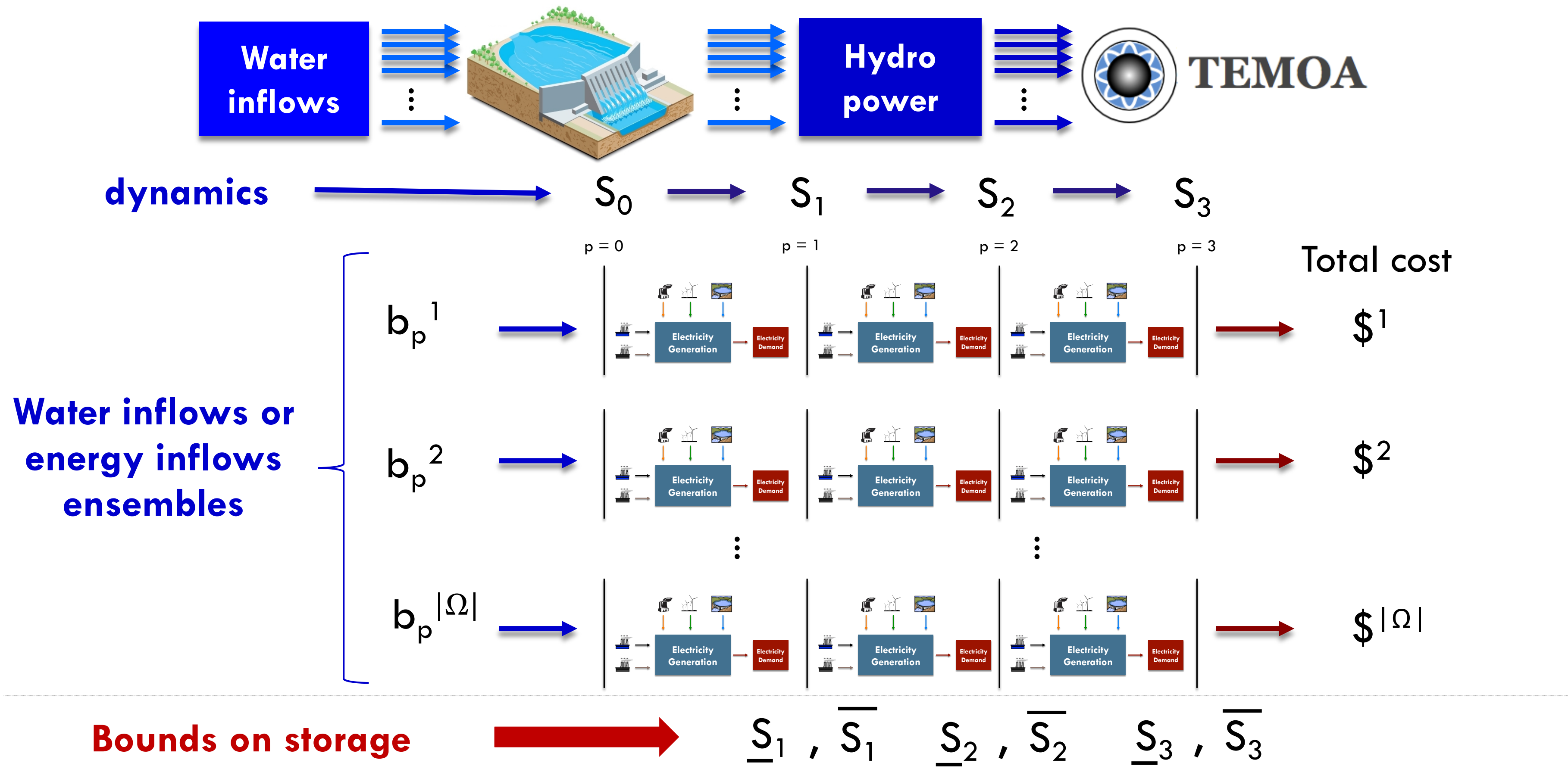
Notation and Previous Model

- A little about notation:
  - We will index time periods by p
  - $\underline{HP}$ and $\overline{HP}$ represents minimum and maximum bounds for hydro power in [aMW]
  - S_p storage values at time period p and $\underline{S}$ and $\overline{S}$ are min and max bounds on storage [hm^3]
  - b_p^1 represents the water inflows in [hm^3] over the course of time period p at hydro plant 1



Enhancing TEMOA Formulation

- Let's talk about a stochastic representation
  - For each scenario $\omega \in \Omega$, the forecasting model model should provide: b_p^{ω}



Enhancing TEMOA Formulation *(cont.)*

- Model needs to carry out information from one month to the other
  - A new decision vector is needed:

    $\mathbf{S_p}$: end of period storage for hydro plants

  - New constraints are needed:

    (Mass balance constraint) $\mathbf{S_p} = S_{p-1} + \mathbf{b_p} - \sum \mathbf{FO_p}$

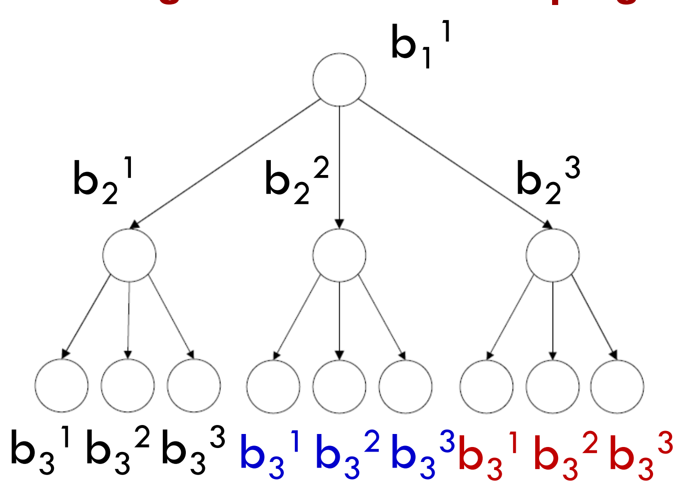
    (Storage bounds) $\underline{S}_p \leq \mathbf{S_p} \leq \overline{S}_p$

    Water inflows

    Water releases

  - By adding that the model has the possibility to make operational recourse actions → **Multi-stage stochastic linear program (SLP-p)**

Scenario tree



General TEMOA Model

$\min_{\mathbf{ACT,FI,FO}}$	**Total Cost = FixedCost + VariableCost**	
s.t.	$\mathbf{ACT}_{p,s,d,t,v} = \sum_{i,o} \mathbf{FO}_{p,s,d,i,t,v,o} \quad \forall\{p,s,d,t,v\} \in \Theta_{\text{activity}}$	Process activity
	$\left(CF_{s,d,t,v} \cdot C2A_t \cdot SEG_{s,d} \cdot TLF_{p,t,v}\right) \cdot \mathbf{CAP}_{t,v} \geq \mathbf{ACT}_{p,s,d,t,v} \quad \forall\{p,s,d,t,v\} \in \Theta_{\text{activity}}$	Technology capacity
	$\sum_{i,t,v} \mathbf{FO}_{p,s,d,i,t,v,c} \geq DEM_{p,c} \cdot DSD_{s,d,c} \quad \forall\left\{p,s,d,c \in C^d\right\} \in \Theta_{\text{demand}}$	Supply-demand
	$\mathbf{FO}_{p,s,d,i,t,v,o} \leq EFF_{i,t,v,o} \cdot \mathbf{FI}_{p,s,d,i,t,v,o} \quad \forall\{p,s,d,i,t \in T - T^s, v, o\} \in \Theta_{\text{flow}}$	Process-level commodity flow
	$\sum_{i,t,v} \mathbf{FO}_{p,s,d,i,t,v,\mathbf{c}} \geq \sum_{t,v,o} \mathbf{FI}_{p,s,d,\mathbf{c},t,v,o} \quad \forall\{p,s,d,c\} \in \Theta_{\text{balance}}$	Global commodity balance
	$\mathbf{S_p = S_{p-1} + \tilde{b}_p - \sum FO_p} \qquad \mathbf{\underline{S}_p \leq S_p \leq \overline{S}_p}$	Water balance and bounds
Random water inflows	Other constraints and bounds,…	

Power Generation Scheduling as SLP-p

A general model for power generation scheduling would be

$$\min_{x_1} \quad c_1 x_1 + E_{b_2|b_1} h_2(x_1, b_2)$$
$$\text{s.t.} \quad A_1 x_1 = B_1 x_0 + b_1$$
$$x_1 \geq 0$$

where, for $p = 2,\ldots,P$

$$\min_{x_p} \quad c_p x_p + E_{b_{p+1}|b_1,\ldots,b_p} h_{p+1}(x_p, b_{p+1})$$
$$\text{s.t.} \quad A_p x_p = B_p x_{p-1} + b_p$$
$$x_p \geq 0$$

x_p: stage p decision variables including: technologies activity (hydro generation, thermal generation), resources activity, water storage at reservoirs

c_p: cost vector related to technology and resource usage

A_p: constraint matrix including supply-demand, process-level commodity flow, global commodity water balance, ...

b_p: stochastic water inflow at each hydro plant and deterministic demand

$B_p x_{p-1}$: storage from last stage

Case Study

Deterministic Case Study

TEMOA Input Parameters Specs

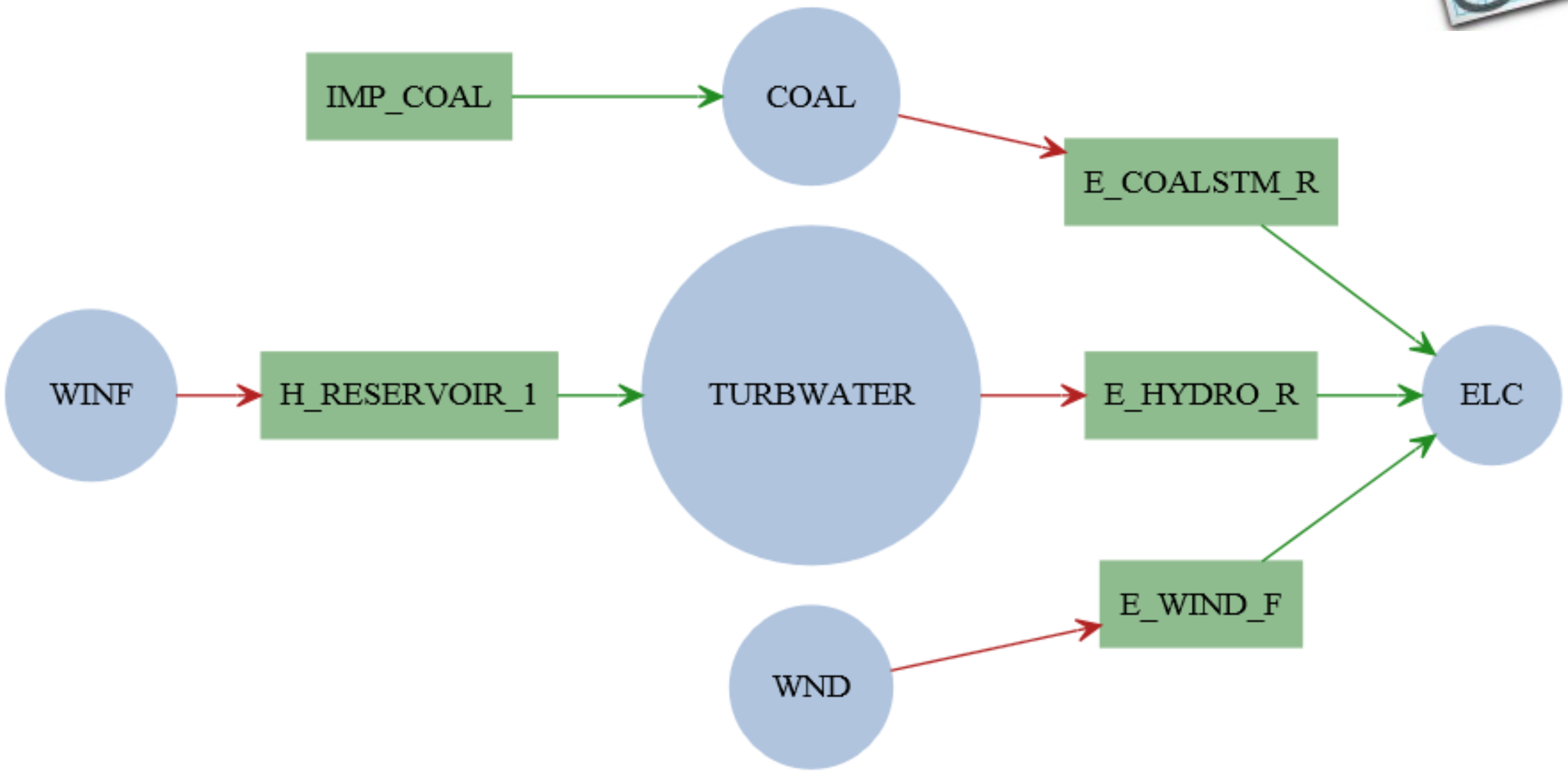
- We are interested in problems for short horizons
- Time horizon: 3 months $\rightarrow P^f = \{1,2,3,4\}$
- Seasons: 4 weeks $\rightarrow S = \{W_1,W_2,W_3,W_4\}$
- Time of the day: 3 slices $\rightarrow D = \{day,night,peak\}$
- Discount rate 1% per month $\rightarrow GDR = 0.01$
- Capacity-activity conversion factor 31.536 **(year)** $\rightarrow$ 2.628 **(month)**

HydroStorage Case Study – Instances

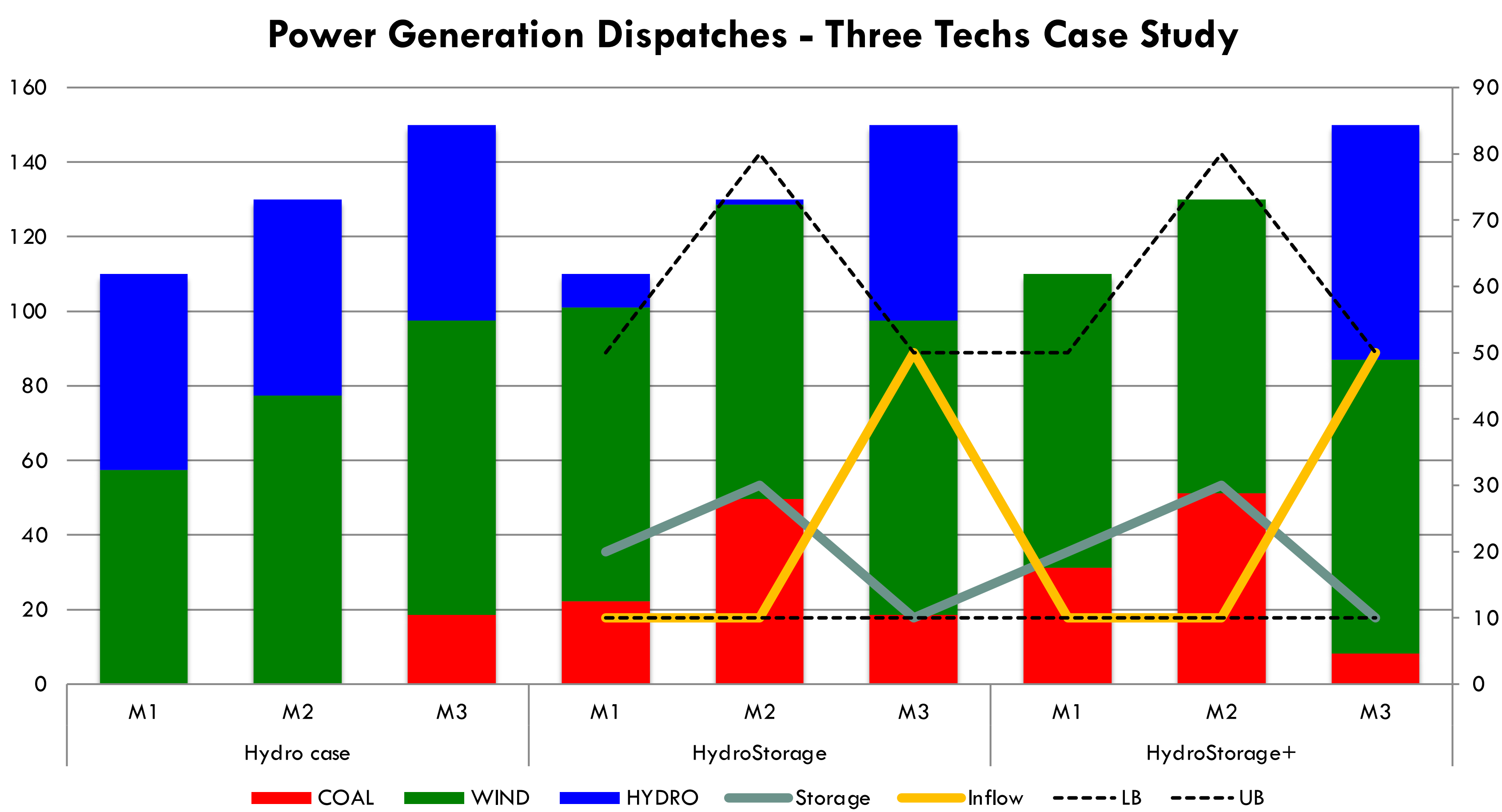
- Case Hydro:
  - DEM_{1c} = 110 [PJ] DEM_{2c} =130 [PJ] DEM_{3c} = 150 [PJ]
  - **Coal thermal plant** MAX_1 = **36[GW]** **Wind Farm** MAX_2 = **100[GW]**
  - **Hydropower** installed capacity = **20[GW]**
  - **Efficiency: Hydro → ELC = 0.9**
- Case HydroStorage:
  - **Hydropower** installed capacity = **20[GW]**
  - **Initial Storage = 10** **Water Inflows** **= [10, 10, 50]**
  - **Efficiency: Reservoir → TurbWater = 1.0**
  - **Thermal Cost in** $P^f = 3$ **increased from 3 → 3.5 [M$/PJ]**
- Case HydroStorage+:
  - **Hydropower** installed capacity = **25[GW]**

Network Representation

- Python script → graphical representation (Graphviz)



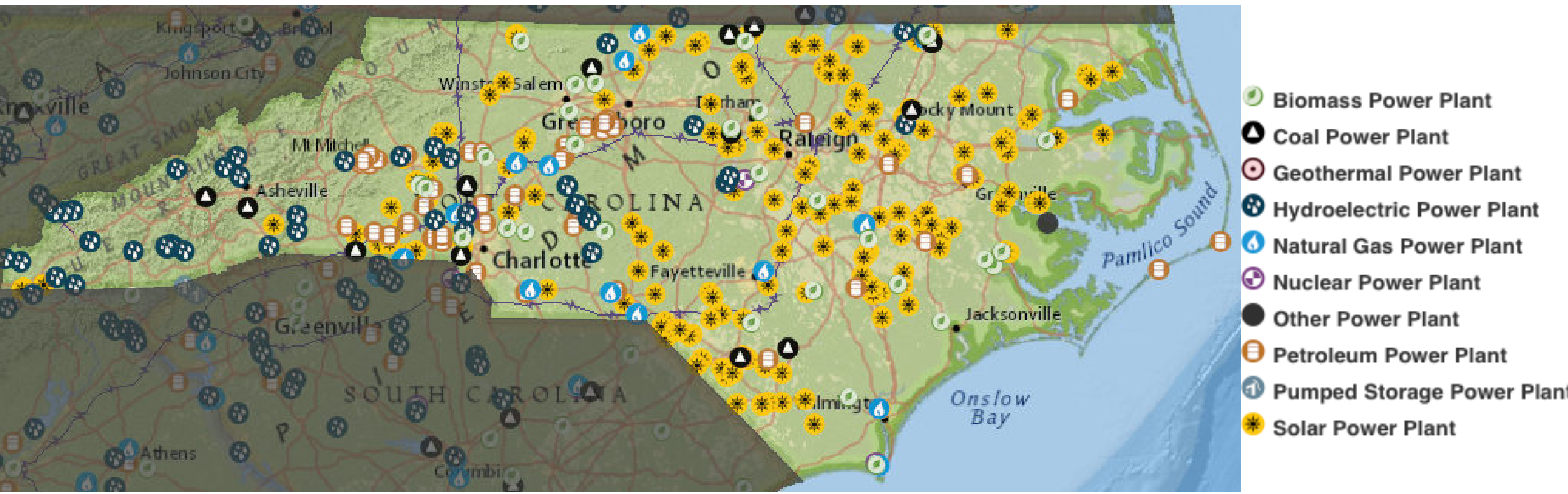
Deterministic Case Study - Results



North Carolina Case Study

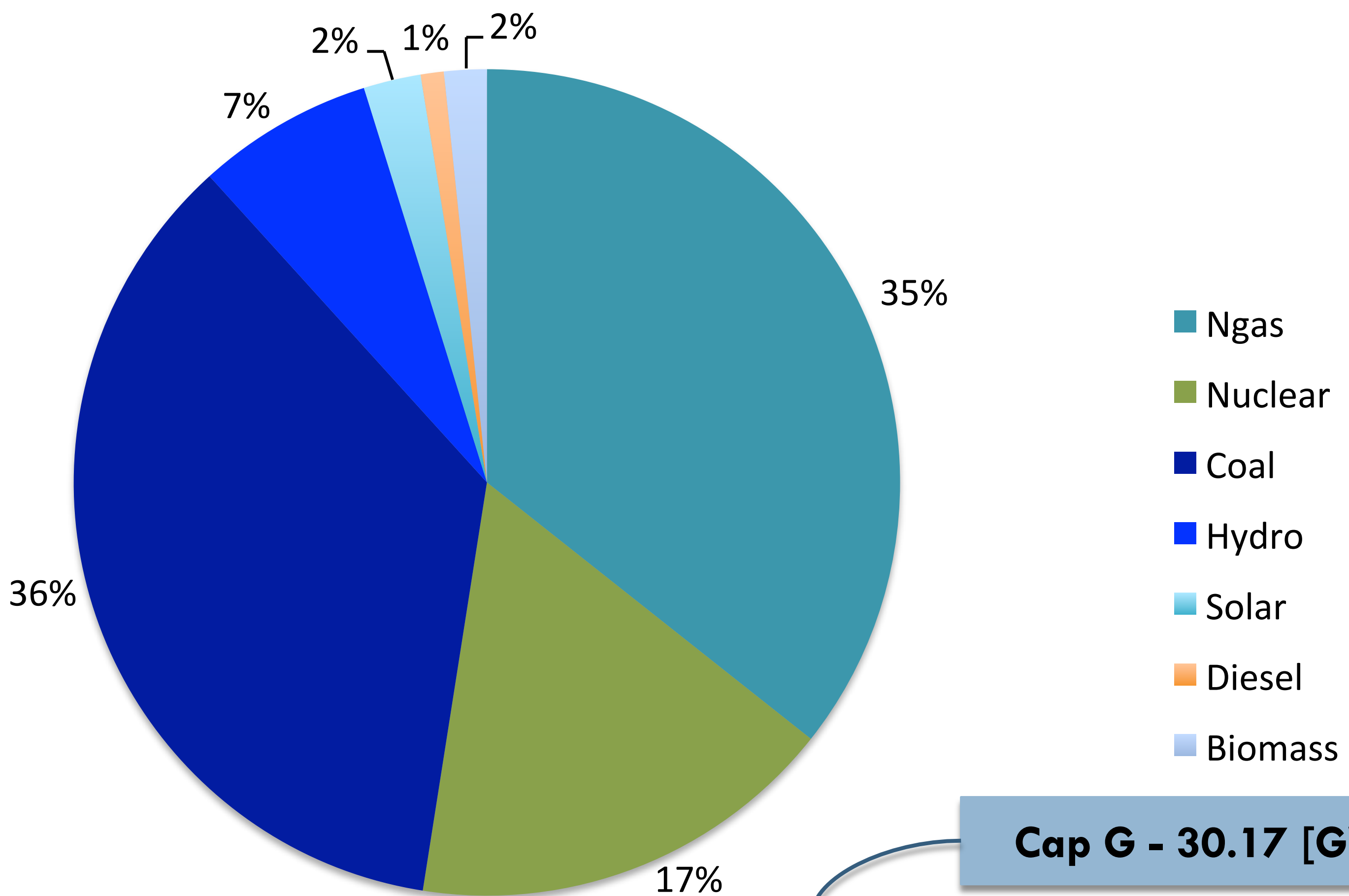
North Carolina State – Case Study

- Input information adapted from EIA database



- We consider only the installed capacity in year 1
- For this case study we aim to solve 4-stage problems

Installed Capacity – NC Case Study



Cap G - 30.17 [GW]

Cap G - 14. 70 [GW]

D - 11.70 [GW]

* After efficiency and capacity factor

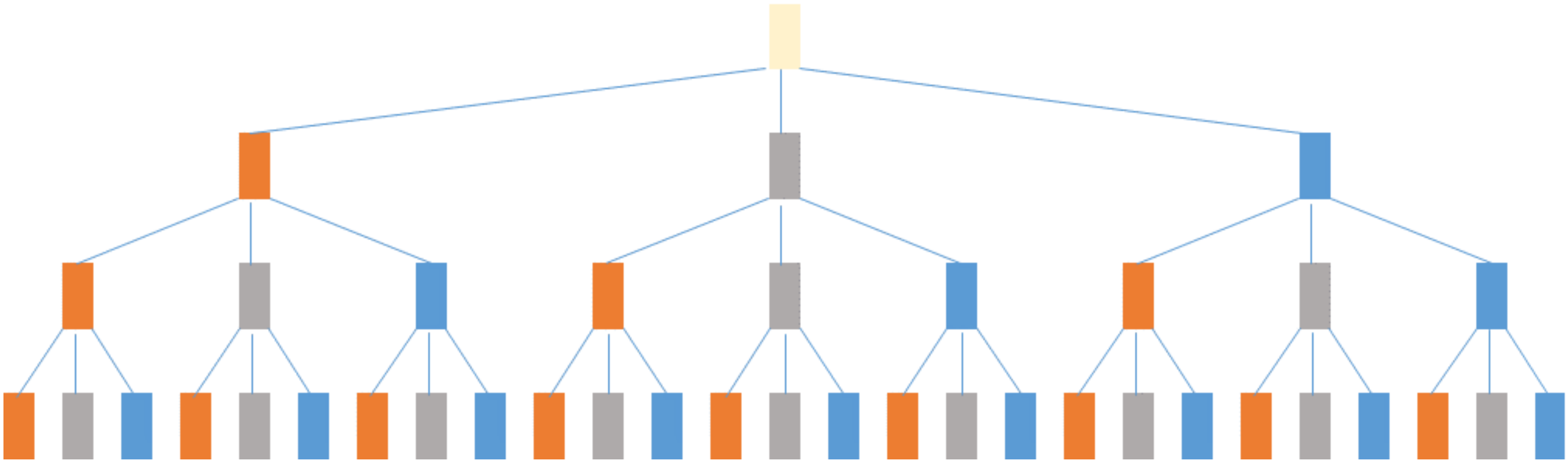
TEMOA Input Parameters Specs

- Time horizon: 4 months → $P^f = \{1,2,3,4,5\}$
- Seasons: 4 weeks → $S = \{W_1, W_2, W_3, W_4\}$
- Time of the day: 4 slices → D = {am,pm,peak,night}
- Discount rate 1% per month → GDR = 0.01
- Capacity-activity conversion factor 2.628 **(month)**
- Demand at each stage:

  DEM_{1c} = 30.75 [PJ], DEM_{2c} =30.75 [PJ], DEM_{3c} = 30.75 [PJ], DEM_{4c} = 30.75 [PJ]
- Base case:
  - **Coal** MAX_1=**10.8[GW]**, **NGas** MAX_2=**10.7[GW]**, **Nuclear** MAX_3=**5.1[GW]**
  - **Hydropower** installed capacity +/- **2[GW]** **& Other = 1.5[GW]**
- **Other cases:** DEM_{1c} = 15.375 [PJ] / DEM_{1c} = 4.3 [PJ] / Reduced water inflows at scenario low

1 [PJ]
↓
277.8[GWh]

Scenario Tree for NC Instance



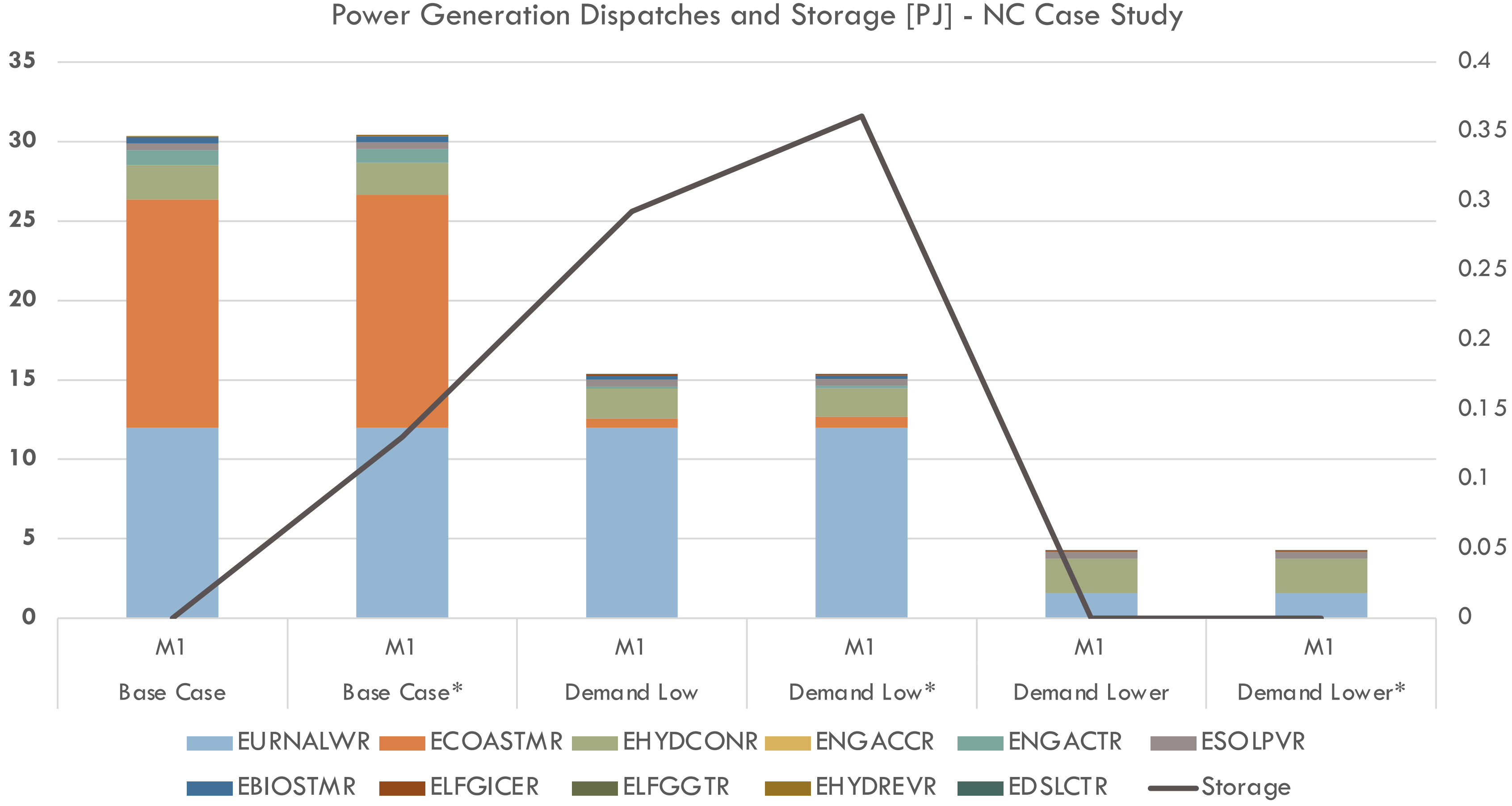
Probabilities estimated using EIA monthly generation data since 2000

		M_H/A_H	0.25	J_H/M_H	0.75
		M_A/A_H	0.625	J_A/M_H	0.2
		M_L/A_H	0.125	J_L/M_H	0.05
A_H/M_A	0.2	M_H/A_A	0.25	J_H/M_A	0.08
A_A/M_A	0.70	M_A/A_A	0.58	J_A/M_A	0.58
A_L/M_A	0.10	M_L/A_A	0.17	J_L/M_A	0.34
		M_H/A_L	0.1	J_H/M_L	0.06
		M_A/A_L	0.5	J_A/M_L	0.56
		M_L/A_L	0.4	J_L/M_L	0.38

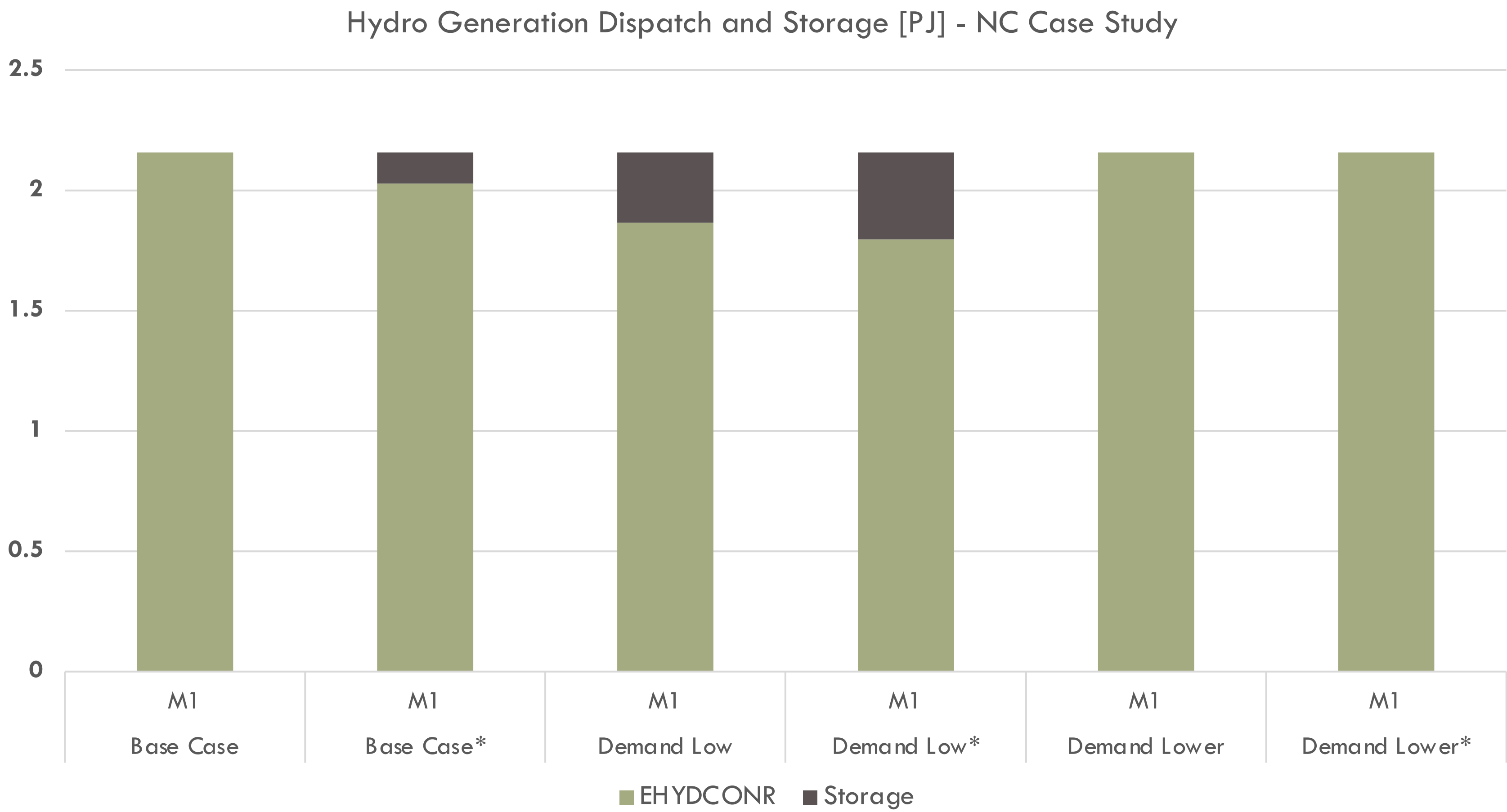
Artificial water inflows produced from generation data
[$10^3 hm^3$-month]
(2.78 → 820.71[aMW])

March	April	May	June
	3.30	3.13	3.65
2.78	2.44	2.04	2.13
	1.92	1.70	1.74

North Carolina Case Study – Results *(cont.)*



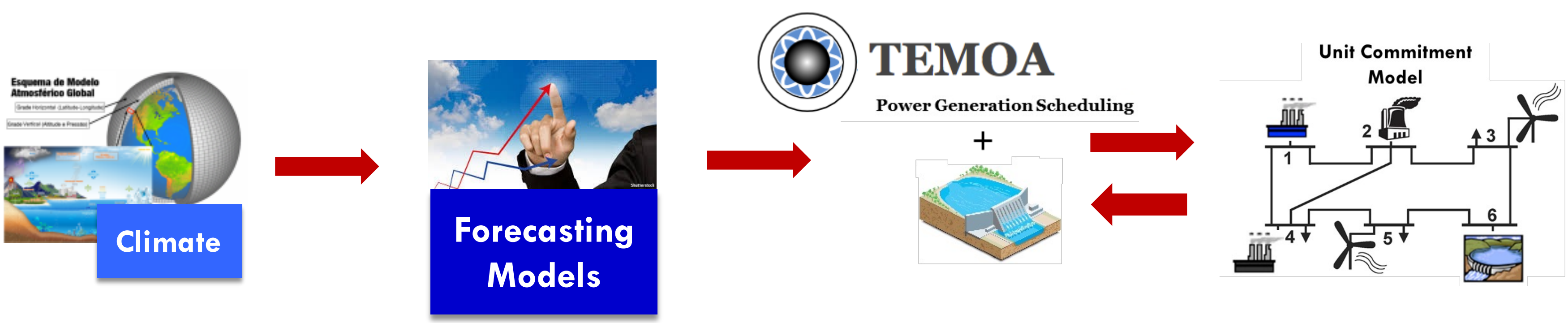
North Carolina Case Study – Results *(cont.)*



Nexts Steps & Final Comments

Next Steps & Final Comments

- Define a balanced study case in terms of a hydro and thermal generation in a system with reservoir storage
- Formulation of a combined framework in a closed-loop form to solve scheduling problem and & unit commitment
- Add climate information to resource supply availability and electricity demand → generate future scenarios
- Represent large-size problems and provide a solution methodology using Sampling-based Decomposition Algorithms



References

- Hunter, K., Sreepathi, S., and DeCarolis, J., ”Modeling for insight Tools for Energy Model Optimization and Analysis (Temoa)”, Energy Economics, 40, 339-349, 2013
- Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., Bazillian, M., Roehrl, A., ”OSeMOSYS: the open source energy modeling system” Energy Policy 39, 5850–5870, 2011
- Hart, W.E., Laird, C., Watson, J.-P., Woodruff, D.L., ”Pyomo - Optimization Modeling in Python”, first ed. Springer, Berlin, 2012
- Pereira, M.V.F., and Pinto, L.M.V.G., “Stochastic Optimization of a Multi-reservoir Hydroelectric System: A Decomposition Approach”, Water Resources Research, Vol.21, No. 6, Pages 779-792, June 1985
- De Queiroz, A.R., “On a Sampling-based Decomposition Algorithm with Application to Hydrothermal Scheduling: Cut Formation and Solution Quality”, PhD dissertation, The University of Texas at Austin, 2011
- Sankarasubramanian, A., Lall, U., Souza Filho, F.A., and Sharma, A., ” Improved water allocation utilizing probabilistic climate forecasts: Short-term water contracts in a risk management framework”, Water Resources Research, v. 45, 1-18, 2009

THANK YOU !

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