



# Aprendizaje y representación aproximada de la información de política de operación contenida en la función de costo futuro de un sistema dinámico

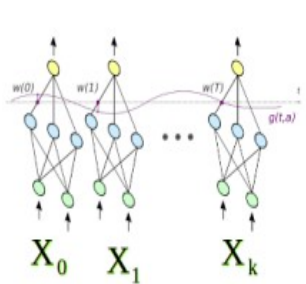
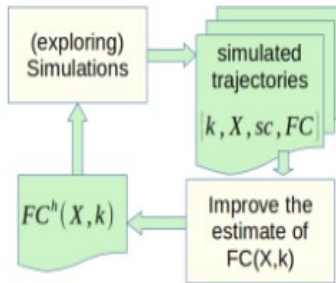
Presentación de avance de tesis de Proyecto de Doctorado en Ingeniería de la Energía.

23 de noviembre de 2023 FING-UdeLaR

Ing. Ruben Chaer.

Tutores:

Dr. Ing. Ignacio Ramírez.

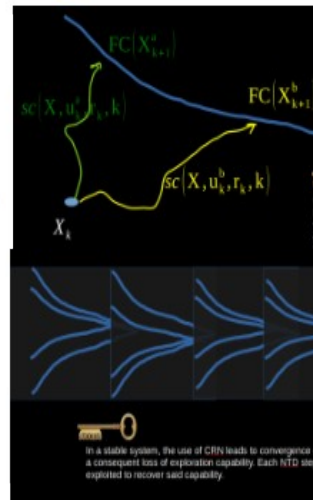


$$L = \sum_{k=0} L_{k+1} + \lambda \sum_k \|\theta_k\|^2 + \beta \sum_{k=2} \|\theta_k - \theta_{k-1}\|^2$$

- Parsimony(t)
  - TD
  - Power series and harmonics
- p=2 : Ridge
- p=1 : Lasso

Approximate the differences instead of the function itself

$$L_{k+1} = \frac{1}{4N^2} \sum_{i+j=k} ((M(X_{i+1}, \theta_i) - M(X_{i+1}, \theta_j)) - (FC_{i+1} - FC_{i+1}))^2$$



# optimal operation of dynamic systems

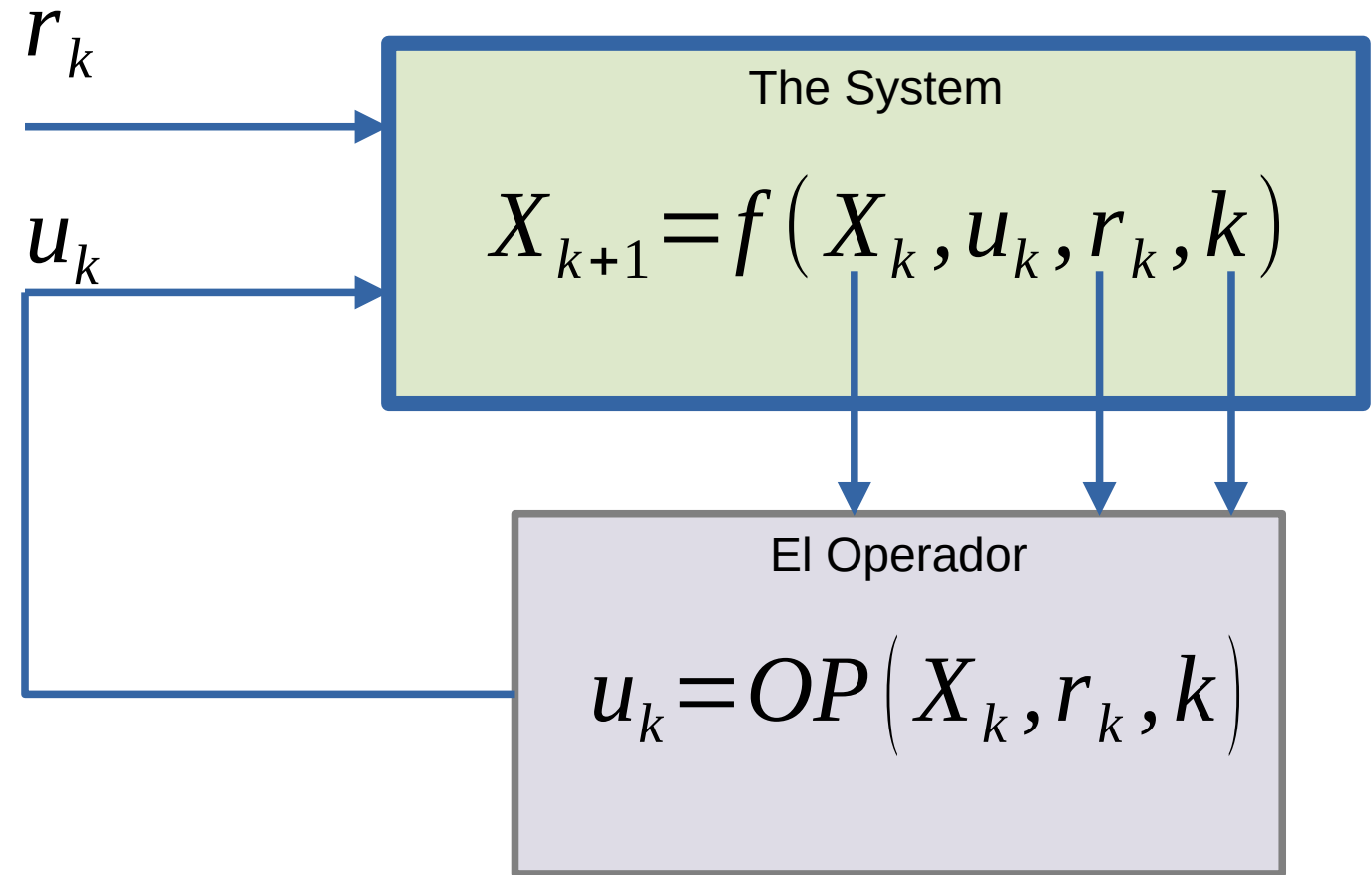
The use of stored resources (water) today reduces the operating costs of the present but increases the operating costs of the future; and vice versa.

An Optimal Policy reduces the expected value of the cost of future operation of the system.

An Optimal Policy balances the effects of actions on future and present costs.



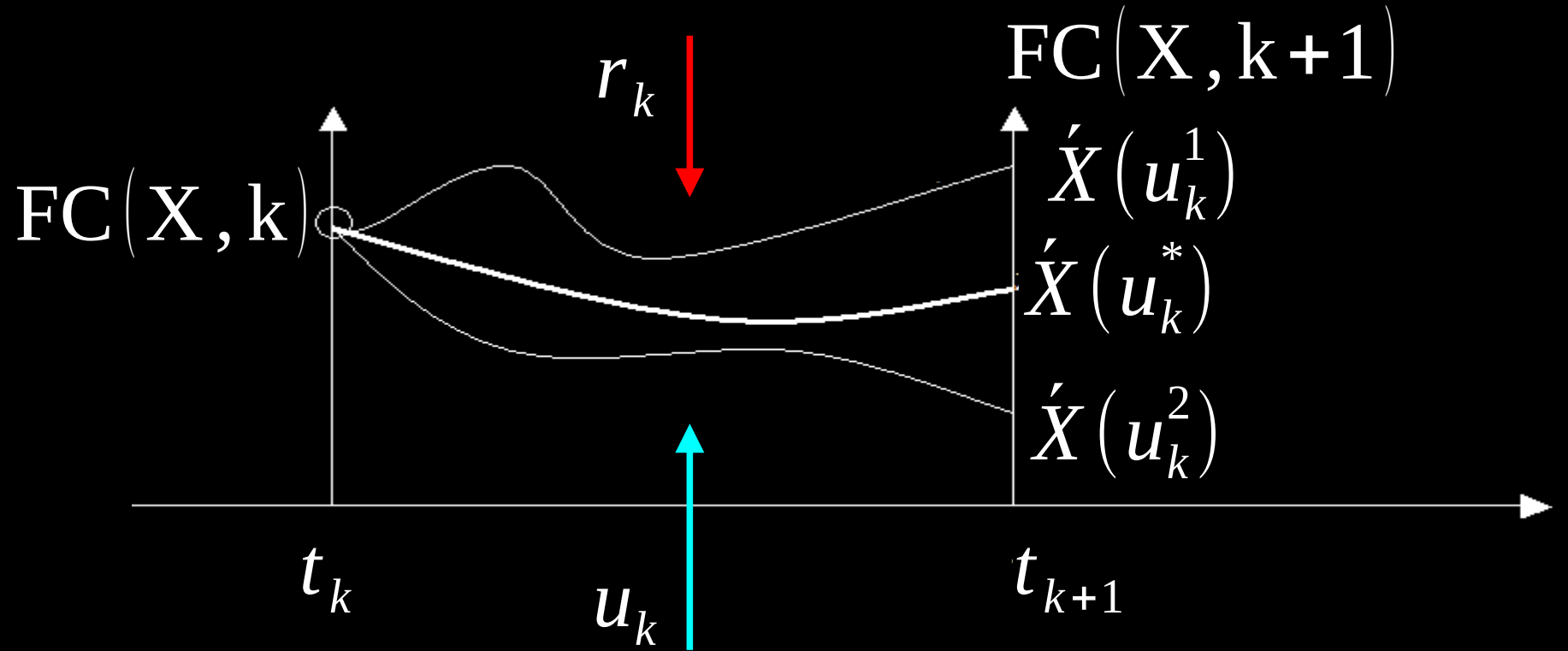
# The Operator and the Operation Policy





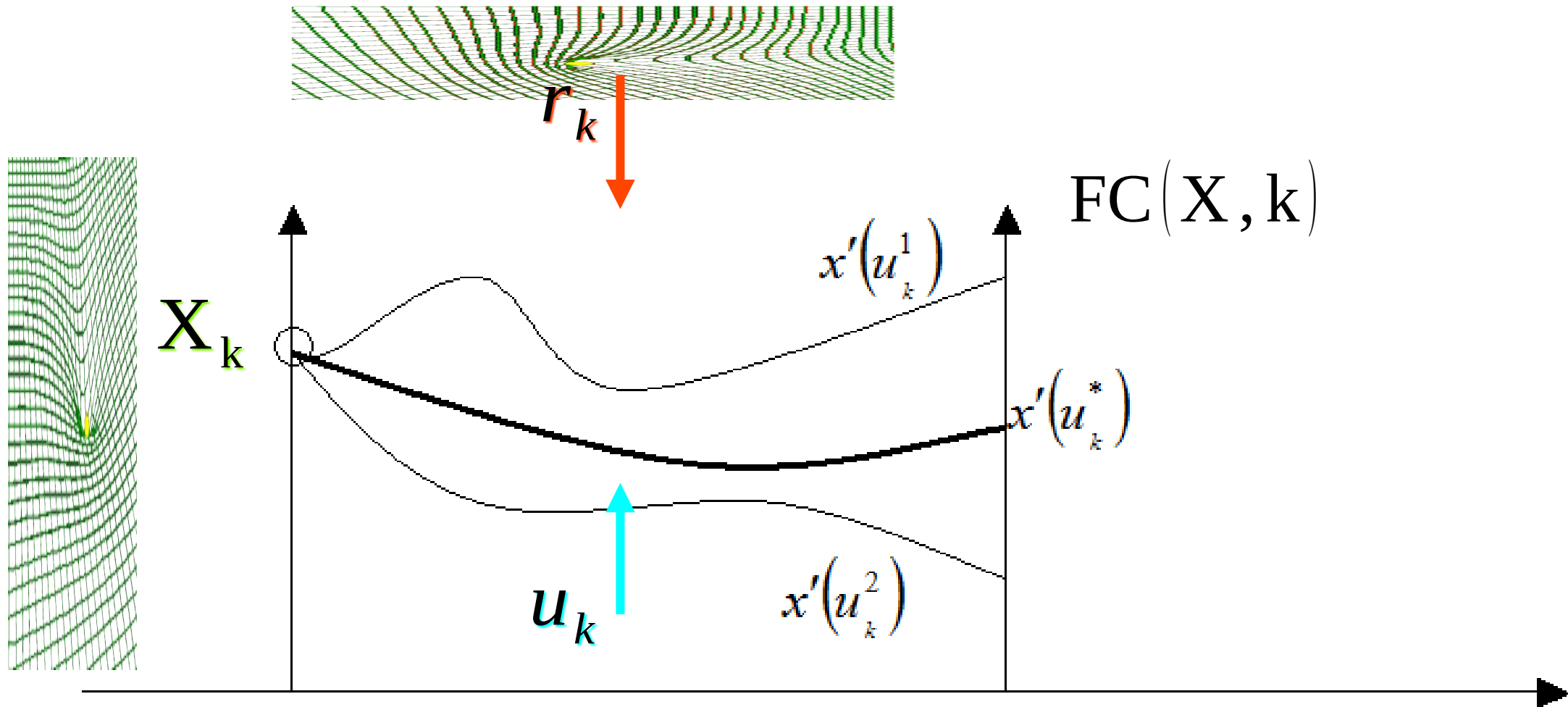
Richard Ernest Bellman (1920–1984)

- **Dynamic Programming 1957.**  
**Bellman recursion**



$$FC(X, k) = \left\langle \min_{u_k} \left\{ sc(X, u_k, r_k, k) + \rho FC(X_{k+1}) \right\} \right\rangle_{\{r_k, r_{k+1}, \dots\}}$$

# Bellman's Curse of Dimensionality



$$Dim(u) \times N_{X_1}^{t_k} \times N_{X_2} \dots \times N_{X_{Dim(X)}} \times N_{r_1}^{t_{k+1}} \times N_{r_2} \dots \times N_{r_{Dim(r)}} \times N_t$$

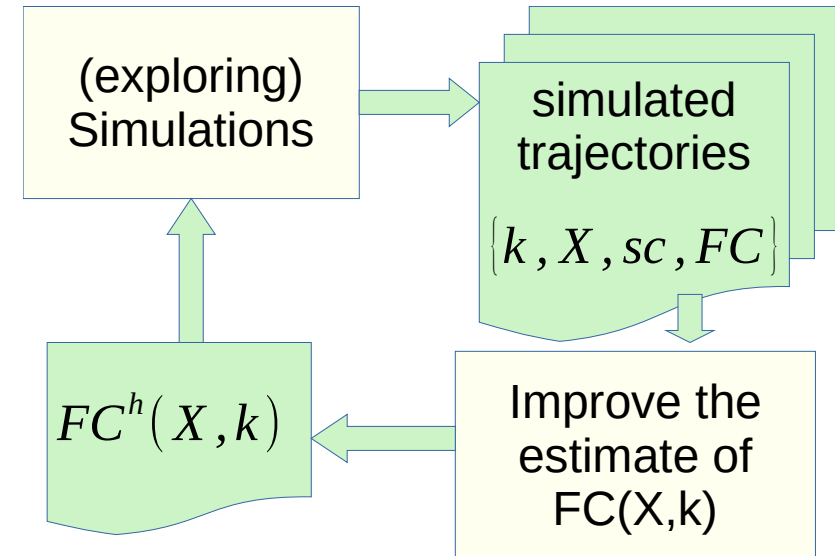
# BR vs. Machine learning of $FC(X,k)$



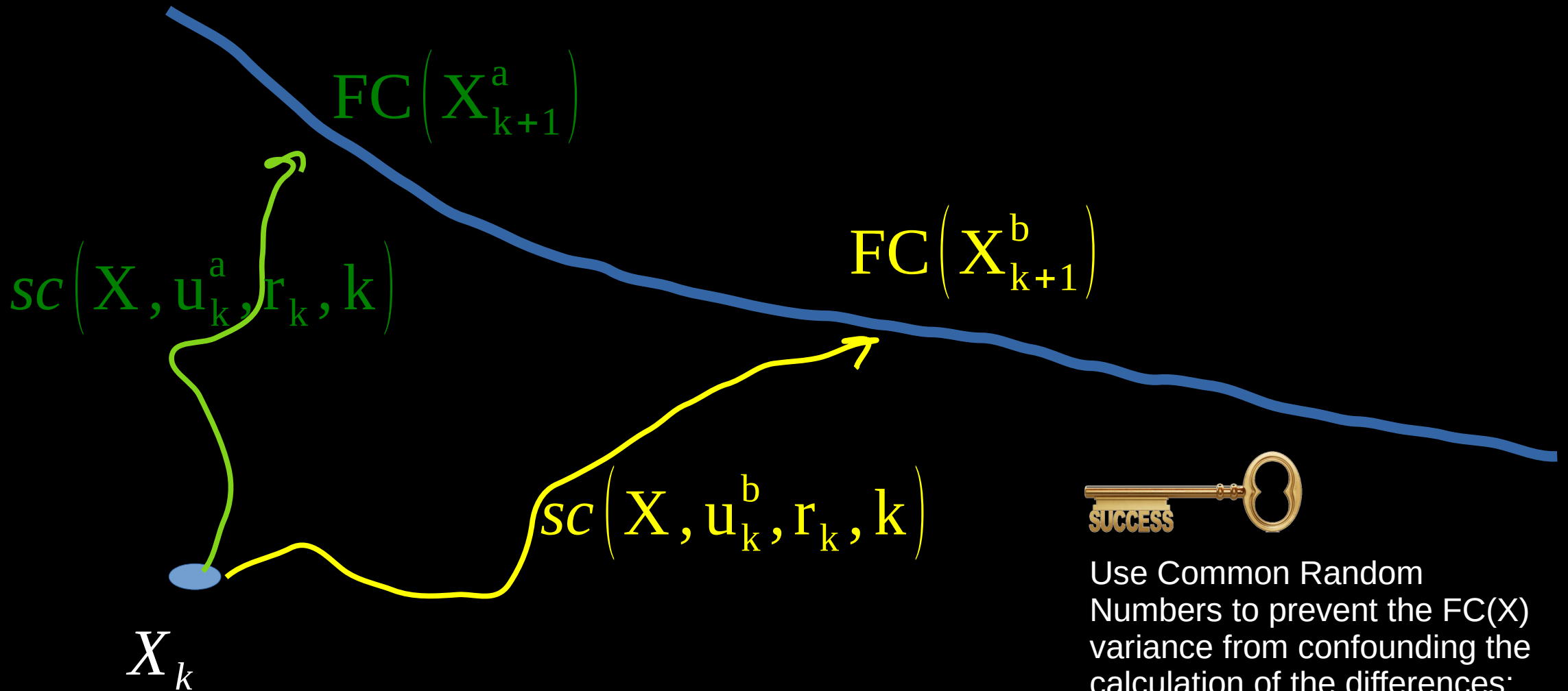
$$\min_u \left\{ sc(X_k, u_k, r_k, k) + FC(X_s, k+1) \right\}$$
$$@ \begin{cases} u \in \Omega(X_k, r_k, k) \\ X_s = f(X_k, u_k, r_k, k) \end{cases}$$



# Learning Loop



# The information is in the $FC(X)$ differences



Use Common Random Numbers to prevent the  $FC(X)$  variance from confounding the calculation of the differences:  $FC(X_a) - FC(X_b)$  at the arrival states

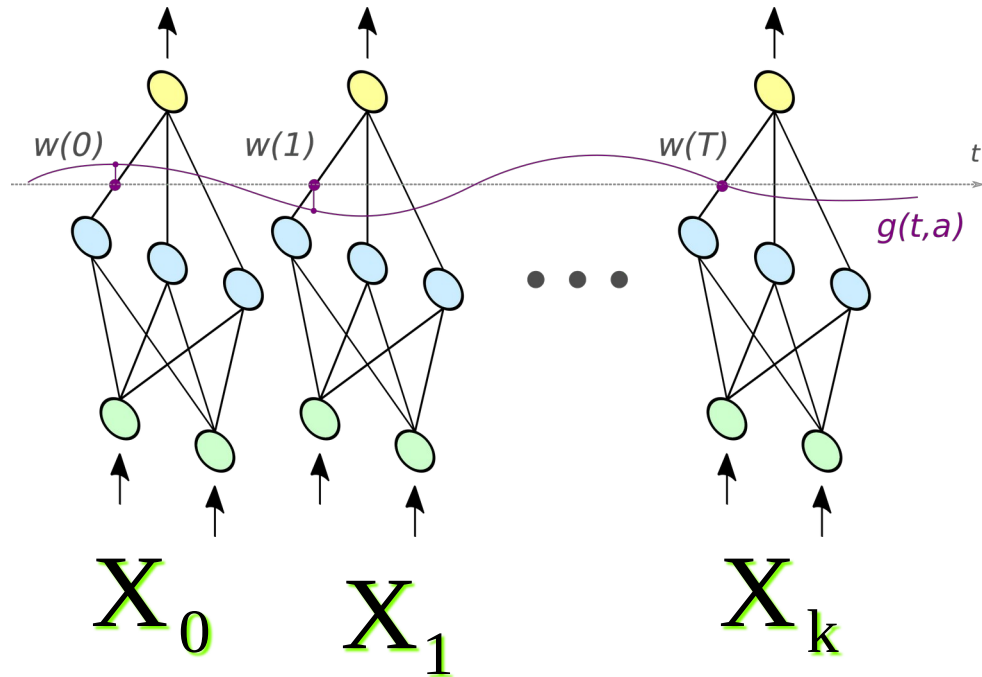


# Exploration Strategies



In a stable system, the use of CRN leads to convergence of trajectories and a consequent loss of exploration capability. Each NTD steps states are exploited to recover said capability.

# FC(X) representation and regularizations



$$L = \sum_{k,g} L_{kg} + \lambda \sum_k \|\theta_k\|^p + \beta \sum_{k=2} \|\theta_k - \theta_{k-1}\|^2$$

- Parsimony(t)
  - TD
  - Power series and harmonics

- p=2 : Ridge
- p=1 : Lasso



Approximate the differences instead of the function itself

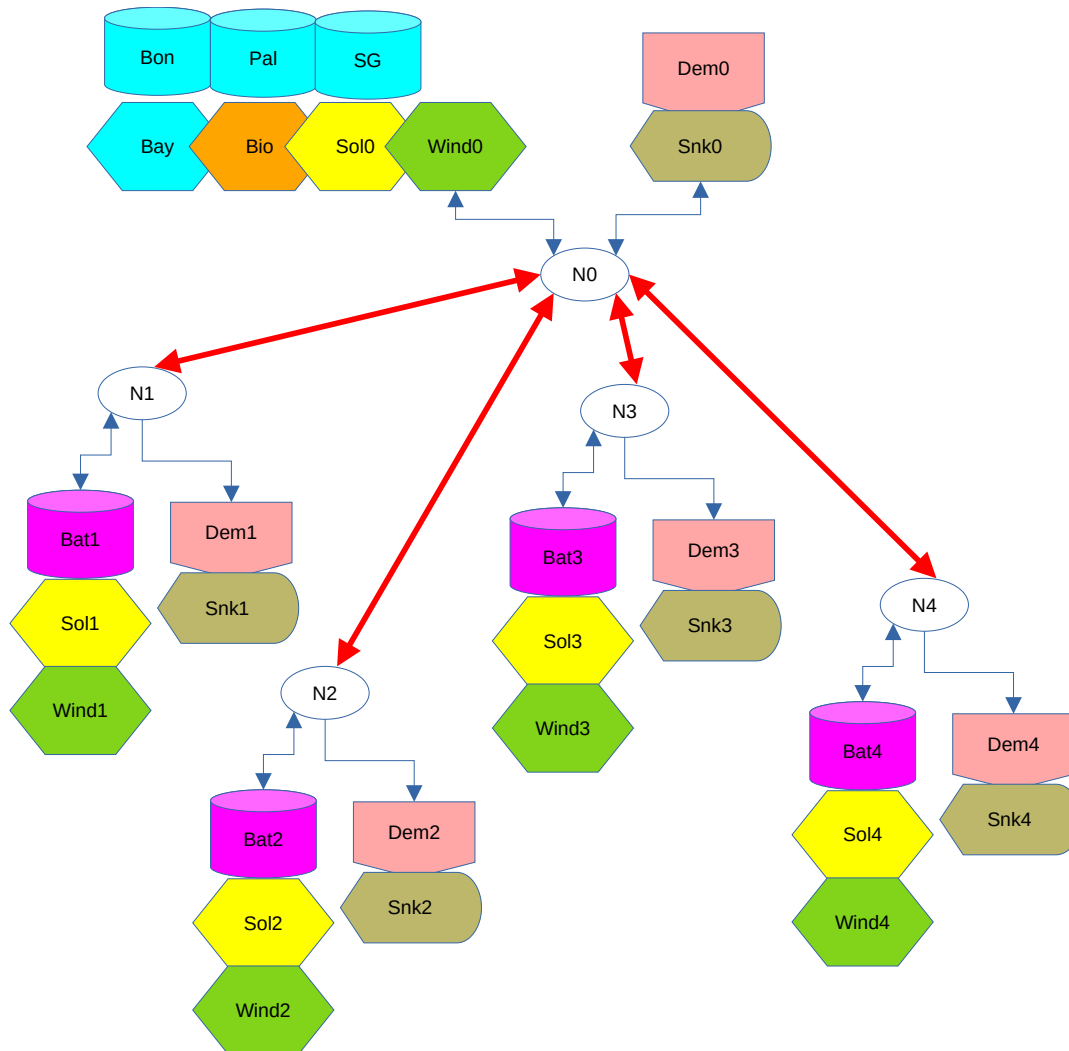
$$L_{kg} = \frac{1}{4N^2} \sum_{i \neq j \in g} ((M(X_{kj}, \theta_k) - M(X_{ki}, \theta_k)) - (FC_{kj} - FC_{ki}))^2$$



**In a continuously operated system, learning is also processed continuously. With the course of each real hour, the vector of neurons is moved, discarding the one corresponding to the elapsed hour and repeating the last neuron of the set to continue in the learning loop**

# Example case. Uruguay 2050

## Hydro+Biomass+Solar+Wind+Battery banks



### 44 state variables:

- 3 lakes
- 40 battery-banks
- Pacific Ocean surface temperature anomaly in region 3.4

### Bellman's Recursion(\*):

- To store the future cost function in floating point, it is necessary 19.7 Tera-bytes
- Solving the recursion on a 48-core computer would take 286 years.

(\*assuming a year and a half with hourly steps and discretizing the state variables in 5 positions)

Less than 12 hours to obtain a reasonable operation of the system!



<https://simsee.org/investigacion/tractorcito.html>



Proyecto ANII FSE\_1\_2017\_1\_144926

## TRACTORCITO

Planificación de inversiones con energías variables, restricciones de red y gestión de demanda.



UNIVERSIDAD  
DE LA REPUBLICA  
URUGUAY



Instituto de Ingeniería Eléctrica - Facultad de Ingeniería - Universidad de la República Oriental del Uruguay.  
Proyecto financiado por el Fondo Sectorial de Energía - ANII 2017.



**Ejecución:** Setiembre 2018 - Setiembre 2020

**Investigadores:** Pablo Soubes, Damián Vallejo, Ximena Caporale, Sergio Martínez y Felipe Palacio.

**Co-responsable científico:** Ignacio Ramirez.

**Responsable científico:** Ruben Chaer.

## Publicaciones específicas asociadas a la tesis

- Machine learning for optimal operation of fully renewable energy systems, - en preparación para el IEEE-IGTD-2023 *(en preparación Deadline 28/11/2022)*
- Learning the optimal joint operation of the energy systems of Uruguay, Brazil, Paraguay and Argentina, R.Chaer et.al Congreso IEEE-GTDLA 2022, 20 Oct. 2022, Colombia. *(Aceptado, pendiente de publicación en la IEEExplorer)*
- Teaching a Robot the optimal operation of an Electrical Energy System with high integration of renewable energies. R.Chaer et. al. Congreso IEEE-URUCON 2021, 24-26 Nov. 2021, Montevideo-Uruguay. *(Aceptado y publicado en la IEEExplorer)*

**Otras actividades que considero proyectan y deben ser consideradas para los créditos**

# Publicaciones 2021-2020

## 2021

- Teaching a Robot the optimal operation of an Electrical Energy System with high integration of renewable energies. R.Chaer et. al. Congreso IEEE-URUCON 2021, 24-26 Nov. 2021, Montevideo-Uruguay.
- Generation Investment Planning and Risk Management in BANI Context. G. Casaravilla, R. Chaer y X. Caporale. Congreso IEEE-URUCON 2021, 24-26 Nov. 2021, Montevideo-Uruguay.
- Mixture Density Networks Per Hour-Month Applied to Wind Power Generation Forecast. D. Vallejo y R. Chaer et. al. Congreso IEEE-URUCON 2021, 24-26 Nov. 2021, Montevideo-Uruguay.
- Long-term planning and characterization of Latin American electrical systems based on their resources. Lorena Di Chiara, Gonzalo Casaravilla, Ruben Chaer. Energy, COVID and Climate Change. 1st IAEE Online Conference, 7-9 Jun, page 1--2- 2021
- Energy transition of Uruguay, Gonzalo Casaravilla, Ruben Chaer, IAEE Energy Forum - Fourth Quarter, page 11--14- 2021.
- Aplicación de SimSEE a la planificación de inversiones de generación eléctrica en República Dominicana. Ruben Chaer. Transforma : Boletín Informativo. Proyecto Transición Energética. República Dominicana, Number 5, page 4--7- Mar. 2021

## 2020

- A technical, economical and regulatory analysis of storage systems incorporation in the Uruguayan electricity market. Virginia Halty, Mario Vignolo, Ruben Chaer. 2020 IEEE PES Transmission & Distribution Conference and Exhibition - Latin America (T&D LA), Montevideo, Uruguay, 28 sep-2 oct, page 1--6- 2020
- Energía hidroeléctrica en Uruguay : País lluvioso con sequías. Gonzalo Casaravilla, Ruben Chaer. Informe elaborado por docentes e investigadores del Grupo Energía Eléctrica del Departamento de Potencia-IIE-FIng-UdelaR , page 1--3- Jul. 2020
- Hourly model of a combined cycle power plant for SimSEE. Vanina Camacho, Ruben Chaer. 2020 IEEE PES Transmission & Distribution Conference and Exhibition - Latin America (T&D LA), Montevideo, Uruguay, 28 sep-2 oct, page 1--5- 2020
- Impacto del COVID19 en la demanda de energía eléctrica de Uruguay. Gonzalo Casaravilla, Ruben Chaer, Ximena Caporale. Informe elaborado por docentes e investigadores del Grupo Energía Eléctrica del Departamento de Potencia-IIE-FIng-UdelaR , page 1--3- Jun. 2020
- Integración de ensambles de pronósticos hidrológicos a las herramientas de operación del sistema eléctrico en Uruguay. Alejandra De Vera, Guillermo Francisco Flieller Alfonso, Magdalena Crisci, Ruben Chaer, Rafael Terra. ENERLAC : Revista de Energía de Latinoamérica y el Caribe, Volume 4, Number 1, page 96--117- Jun. 2020
- Introduction of ensemble based forecasts to the electricity dispatch simulator SimSEE . Guillermo Francisco Flieller Alfonso, Ruben Chaer. 2020 IEEE PES Transmission & Distribution Conference and Exhibition - Latin America (T&D LA), Montevideo, Uruguay, 28 sep-2 oct, page 1--6- 2020.
- 
- Mixture density networks applied to wind and photovoltaic power generation forecast. Damián Vallejo, Ruben Chaer. 2020 IEEE PES Transmission & Distribution Conference and Exhibition - Latin America (T&D LA), Montevideo, Uruguay, 28 sep-2 oct, page 1--5- 2020.
- Planning of generation investments with risks of severe infrequent events. Gonzalo Casaravilla, Ruben Chaer, Ximena Caporale. 2020 IEEE PES Transmission & Distribution Conference and Exhibition - Latin America (T&D LA), Montevideo, Uruguay, 28 sep-2 oct, page 1--6- 2020.
- Pumped storage case study in Uruguay : Simulation and value. Federico Sanz, José Cataldo, Ruben Chaer. 2020 IEEE PES Transmission & Distribution Conference and Exhibition - Latin America (T&D LA), Montevideo, Uruguay, 28 sep-2 oct, page 1--4- 2020.



# Participación en talleres/congresos como expositor invitado.

Set-2020-Montevideo-Uruguay (modalidad virtual). "VISION FOR THE FUTURE" - IEEE PES Transmission and Distribution Conference and Exposition – Latin America [T&D LA 2020],. Tutorial: “Optimal Dispatch of High-Penetration Renewable Energy Integrated Power System”.

- Nov-2020 Quito-Ecuador (virtual modality). V Energy Week - Olade - BID. Participation as a guest to the panel: Renewable Energies - Wind future in the region, flexibility of electrical systems.
- Nov-2021 – (virtual mode) IEEE-URUCON 2021. Tutorial: “Despacho óptimo de energía con asimilación de pronósticos”.
- May-2021- (virtual mode) Mexico WindPower. Participation as a guest to the panel: WHERE IS THE ENERGY POLICY GOING? INTERNATIONAL CASES LESSONS LEARNED, THE CASE OF MEXICO
- Marzo 2020 - Mexico WindPower. Participación como invitado en el panel: CÓMO GARANTIZAR UNA RED ELÉCTRICA SÓLIDA Y CONFIABLE PARA LAS EE.RR. MÉXICO.
- Set-2020-Montevideo-Uruguay (modalidad virtual). "VISION FOR THE FUTURE" - IEEE PES Transmission and Distribution Conference and Exposition – Latin America [T&D LA 2020],. Tutorial: “Optimal Dispatch of High-Penetration Renewable Energy Integrated Power System”.
- Nov-2020 Quito-Ecuador (modalidad virtual). V Semana de la energía - Olade - BID. Participación como invitado al panel: Energías Renovables - Futuro eólico en la región, flexibilidad de sistemas eléctricos.
- 2019, March 10-12. 7th ELAEE - 7th Latin American Energy Economics Conference. Participation as invited speaker in the "Workshop: Integrating Renewable Energies in power systems in Central America".

# Participación como revisor:



Institute of Electrical and Electronics Engineers  
2018 IEEE PES Transmission & Distribution Conference and Exhibition Latin America  
*Sustainable Electric Energy for the Future of Latin America*

The 2018 IEEE PES T&D LA Technical Committee certifies this recognition as REVIEWER to:

**Ruben Chaer**

The Conference was held in Lima on September 18<sup>th</sup> to 21<sup>st</sup>, 2018

Lima, September 21<sup>st</sup>, 2018.



**Santiago L. León Gómez**  
Conference Chair  
2018 IEEE PES T&D LA

**Jorge Lafitte Vega**  
Technical Program Chair  
2018 IEEE PES T&D LA



Panamá 11 de noviembre de 2022

Estimado revisor técnico

**Rubén Chaer**

Administración del Mercado Eléctrico (ADME)

En nombre del Comité Organizador de la XL Convención de Centro América y Panamá (CONCAPAN 2022), reconocemos y agradecemos su participación como miembro del Programa Técnico, el cual tuvo la responsabilidad de revisar los artículos sometidos a nuestra conferencia. Valoramos su participación como evaluador ya que su contribución nos permitió mantener el alto nivel de las conferencias técnicas en CONCAPAN.

Esperamos seguir en contacto con usted y contar con su apoyo en futuras versiones de este prestigioso evento regional del IEEE.

Atentamente,

**Enrique Tejera**  
Presidente del Comité Organizador  
CONCAPAN 2022  
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# 8° ELAEE

ENCUENTRO LATINOAMERICANO DE ECONOMÍA DE LA ENERGÍA

20 - 22 NOV > 2022

BOGOTÁ, COL.

## Artificial intelligence applied to the optimal dispatch of decarbonized systems, towards 2050

( another episode of the series: "Fighting Bellman's Curse")

8th ELAEE

Ruben Chaer

18 de Noviembre 2022

Abstract: A perspective is given of where the systems are evolving and the need to incorporate new techniques, such as Artificial Intelligence for efficient management of electricity generation systems.



**IEEE PES  
GTD**  
CONFERENCE & EXPOSITION

Virtual Edition - Latin America - 2022



**“11th IEEE PES Generation, Transmission and Distribution Conference & Exposition Virtual 2022 - Latin America”**

# Learning the optimal joint operation of the energy systems of Uruguay, Brazil, Paraguay and Argentina ( Fighting the Bellman Curse - Episode 2 )



Ruben Chaer <[rchaer@simsee.org](mailto:rchaer@simsee.org)>  
October 20 - 2022



Inteligencia Artificial Aplicada



# Simulación de la operación óptima de los sistemas electro-energéticos de Uruguay, Brasil, Paraguay y Argentina en la plataforma SimSEE.

( otro episodio de la serie: “Luchando contra La Maldición de Bellman” )

*Charlas del Capítulo de PES&IM-IEEE-Uruguay*

*Ruben Chaer  
3 de Noviembre 2022  
11:00 GMT-3*

*Resumen:* Se presenta la incorporación de Inteligencia Artificial a la plataforma SimSEE que hace posible la solución de operación óptima aproximada del conjunto de sistemas creando una política de operación para los 75 embalses considerados. La presentación hace foco en los aspectos metodológicos.

*Webinar (gratis), registro:*

<https://events.vtools.ieee.org/event/register/328042>

