Degradation-Conscious Model predictive Control For Marine Solid Oxide Fuel Cells

Seminar 2024
Health Aware and Safe Control
Learning & Design for Dynamic Systems

Paris, 19-11-2024

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- Introduction
- Solid Oxide Fuel Cells
- Proposed method
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Shaping the Future of Maritime Systems: Autonomy and Sustainability

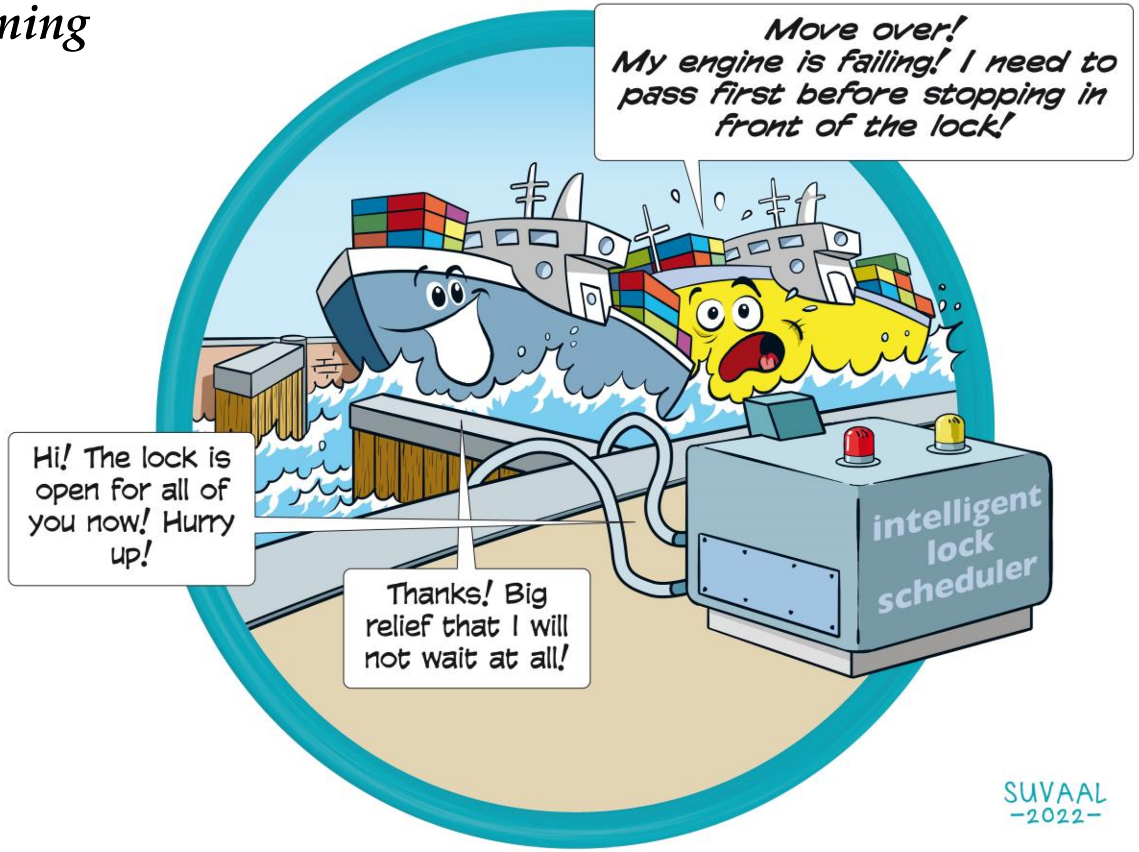
Goals	**Transition to Autonomy**	**Achieving Zero Emissions**
Challenges	• Nonlinear vessel dynamics and interconnections. • Evolving conditions: obstacles, weather, human behavior. • Faults in sensors, actuators, and systems. • Adhering to international regulations (e.g., COLREGS).	• Reducing environmental impact • Managing diverse vessel types, traffic, and logistics. • Integrating sustainable energy solutions

Safe-NET

Safe AutoNomous MaritimE Transport Group

> *"Enhance the autonomy of the maritime transport aiming to ensure safety against significant uncertainties and unexpected events"*

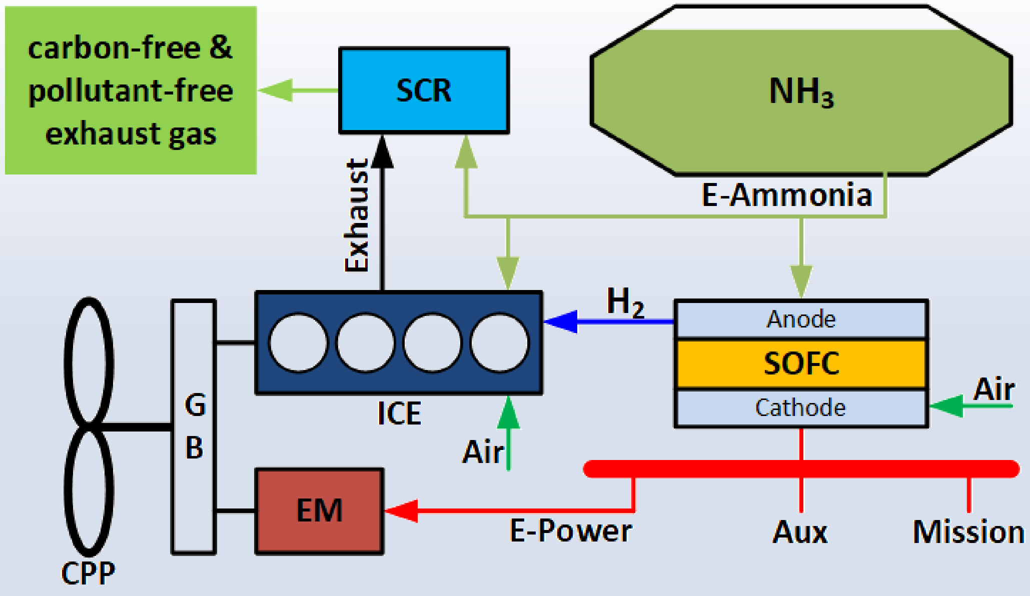
1. **Advancing Safe Autonomy**: Driving digitalization and automation across all maritime systems while prioritizing safety.
2. **Sustainability and Efficiency**: Enabling greener, more efficient, and reliable maritime transport systems.
3. **Research Methodology**: Integrating modeling, control, monitoring, and cyber-physical-human frameworks, validated through real-world applications.

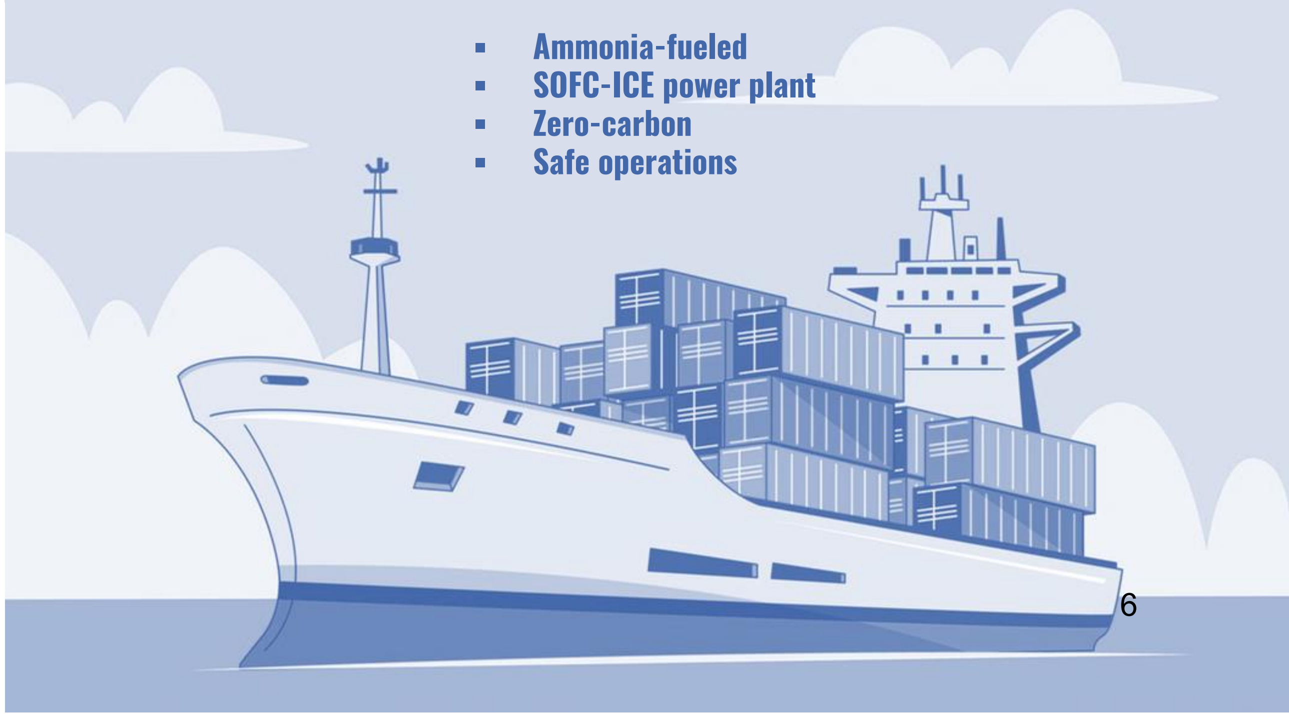


AmmoniaDrive project

The AmmoniaDrive project aims to reduce shipping industry carbon emissions by developing a new ship paradigm that will be fueled by ammonia.

Who?	AmmoniaDrive consortium: 6 **universities**, 3 **research centers** and 10+ **private companies**
What?	**Design** a new **ship concept** fueled by ammonia
Why?	**Decarbonize** shipping industry
How?	Development of a **hybrid powerplant** based on **SOFC-ICE** technologies



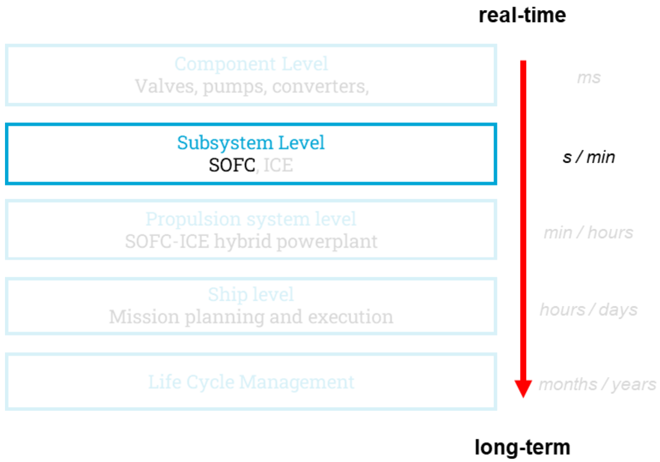


- Ammonia-fueled
- SOFC-ICE power plant
- Zero-carbon
- Safe operations

Maintenance-aware multi-level control for ammonia-powered ships

Promoter
Prof. dr. R.R. Negenborn, TU Delft
Daily supervisor
dr. Vasso Reppa, TU Delft

The main goal is to develop smart strategies to **control** and to **monitor** the **operation** of the Ammoniadrive novel ship, which includes many **non-proven subsystems** in new configurations.



real-time

Component Level
Valves, pumps, converters,

Subsystem Level
SOFC, ICE

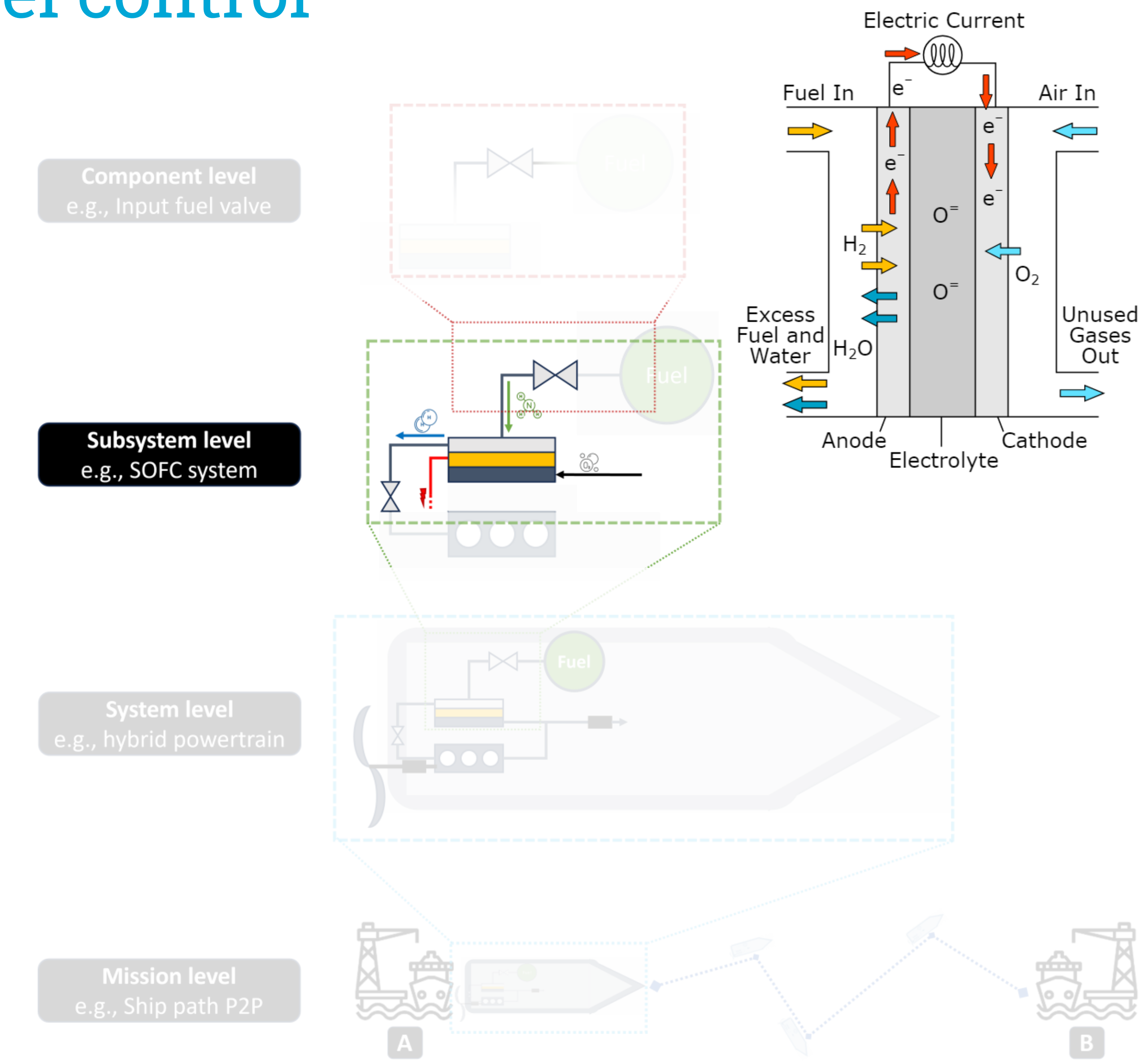
Propulsion system level
SOFC-ICE hybrid powerplant

Ship level
Mission planning and execution

Life Cycle Management

ms
s / min
min / hours
hours / days
months / years

long-term



Component level
e.g., Input fuel valve

Subsystem level
e.g., SOFC system

System level
e.g., hybrid powertrain

Mission level
e.g., Ship path P2P

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Solid Oxide Fuel Cells

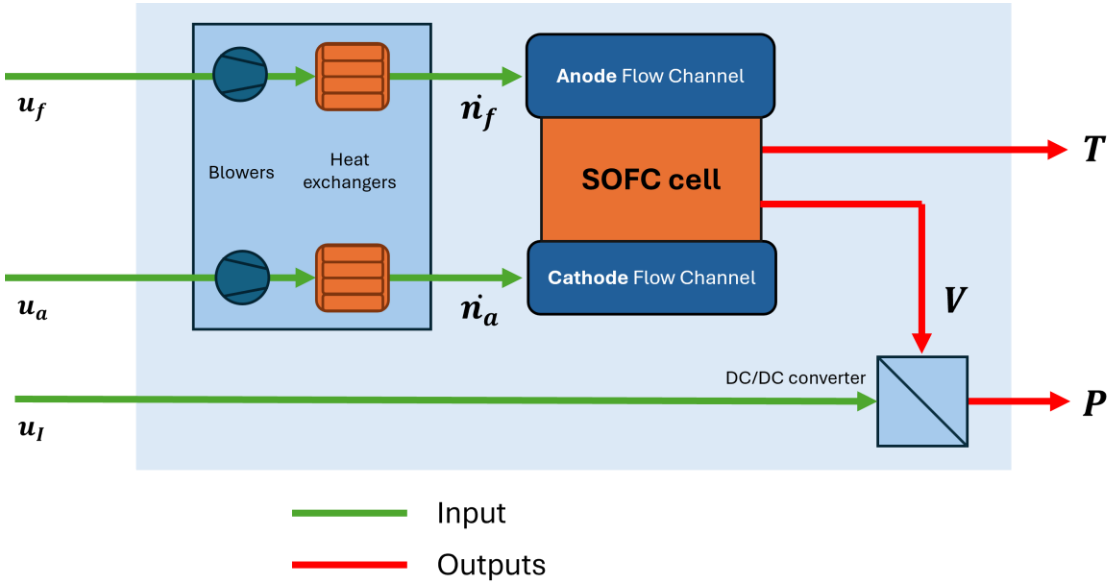
SOFCs are **electrochemical conversion devices** that generate **electricity** by **oxidizing** a **fuel**, such as hydrogen.

Unlike PEM fuel cells, they do not require pure hydrogen and can use **fuels** like **H_2, CH_4, NH_3, and hydrocarbons**.

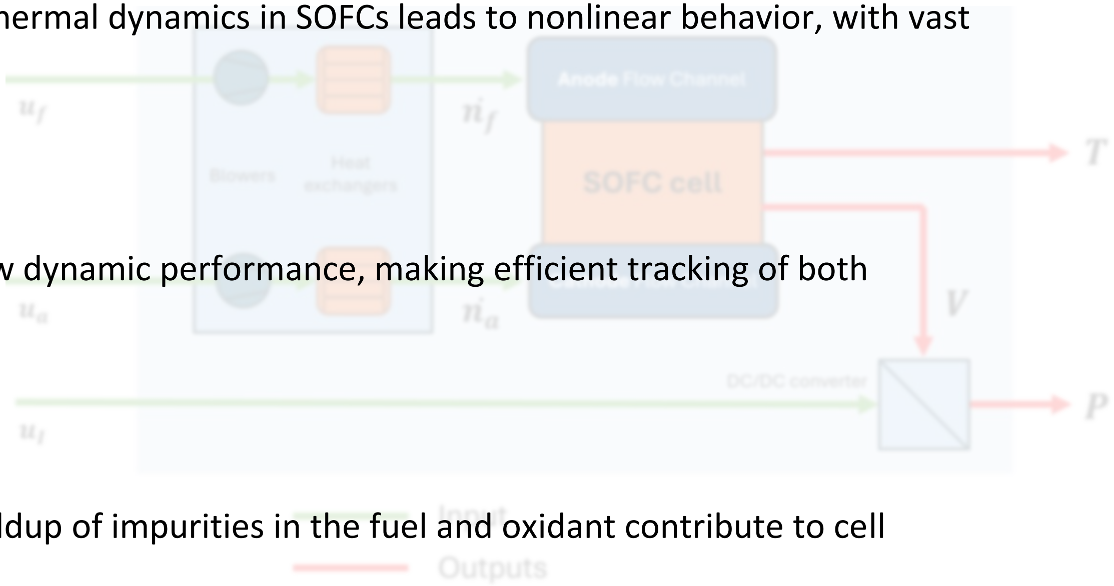
They operate at **high temperatures** and achieve **efficiencies up to 60%**, or higher in combined systems.

Applications:

- **Power Plants**
- **Vehicles**
- **Ships**



Challenges*



Nonlinear Behavior
The mismatch between fast electrochemical reactions and slow thermal dynamics in SOFCs leads to nonlinear behavior, with vast dynamics and limited adaptability to rapid load changes.

Dynamic tracking
The system's complexity and operational constraints result in slow dynamic performance, making efficient tracking of both temperature and power generation highly challenging for SOFCs.

Longevity and degradation
Thermal cycling, material fatigue, chemical reactions, and the buildup of impurities in the fuel and oxidant contribute to cell degradation over time, reducing their longevity.

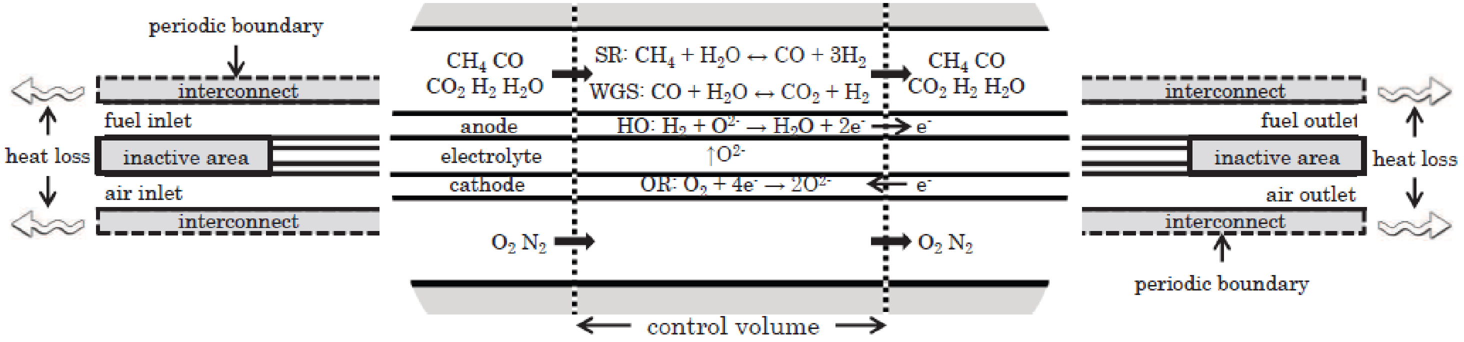
*Associated Literature review in annex

Dynamical model

SOFC dynamics is governed by two main processes: the **energy balance**, which determines cell temperature, and the **electrochemical reactions**, which dictate **voltage output**.

Various models exist in literature, for our study, we utilized a reduced-order model (ROM)*.
Key features:

- **Constant temperature** throughout the cell
- Accurate **chemical process representation** while maintaining model efficiency.



*__A reduced-order model of a solid oxide fuel cell stack for model predictive control__
L. van Biert et al., 2022

Dynamical model

Energy Balance

$$\frac{dT}{dt} = \frac{1}{\bar{c}_p}\left(\underbrace{\sum_{\substack{i\in\mathcal{S},\\ j\in\mathcal{F}}}\left(n_j\bar{K}_i h_i(\bar{T}_i) - \left(n_j\bar{K}_i + \sum_m \bar{\nu}_{i,m} r_m\right) h_i(T)\right)}_{\text{Enthalpy balance}} - \overbrace{IV}^{\text{Electric power}} - \underbrace{\bar{\lambda}(T - \bar{T}_a)}_{\text{Heat Losses}}\right)$$

Chemical species involved $\mathcal{S} := \{\underbrace{\mathrm{CH_4}, \mathrm{CO_2}, \mathrm{CO}, \mathrm{H_2O}, \mathrm{H_2}}_{\text{fuel}}, \underbrace{\mathrm{O_2}, \mathrm{N_2}}_{\text{air}}\}$

Chemical reactions in the cell

$CH_4 + H_2O \rightleftharpoons 3H_2 + CO$ Methane steam reforming

$CO + H_2O \rightleftharpoons H_2 + CO_2$ Water Gas Shift

$H_2 + \frac{1}{2}O_2 \Rightarrow H_2O$ Hydrogen oxydation

Dynamical model

Electrochemistry $$V = \underbrace{-\frac{\Delta g}{2\overline{F}} + \frac{\overline{R}T}{2\overline{F}}\ln(Q)}_{\text{Nernst Voltage}} - \left.\frac{IR_a}{\overline{A}}\right\} \text{Ohmic losses}$$

Reaction Quotient $$Q = \frac{\left(n_{\mathrm{H2}} + \sum_m \bar{\nu}_{\mathrm{H2},m} r_m\right)\left(n_{\mathrm{O2}} + \sum_m \bar{\nu}_{\mathrm{O2},m} r_m\right)^{\frac{1}{2}}}{n_{\mathrm{H2O}} + \sum_m \bar{\nu}_{\mathrm{H2O},m} r_m}$$

Physical constraints

$$\mu_f = \frac{I}{2\overline{F}\left(4n_{\mathrm{CH_4}} + n_{\mathrm{CO}} + n_{\mathrm{H_2}}\right)}, \quad 0 \leq \mu_f \leq 1$$ Fuel utilization

$$\mu_a = \frac{I}{4\overline{F}n_{\mathrm{O_2}}}, \quad 0 \leq \mu_a \leq 1$$ Air utilization

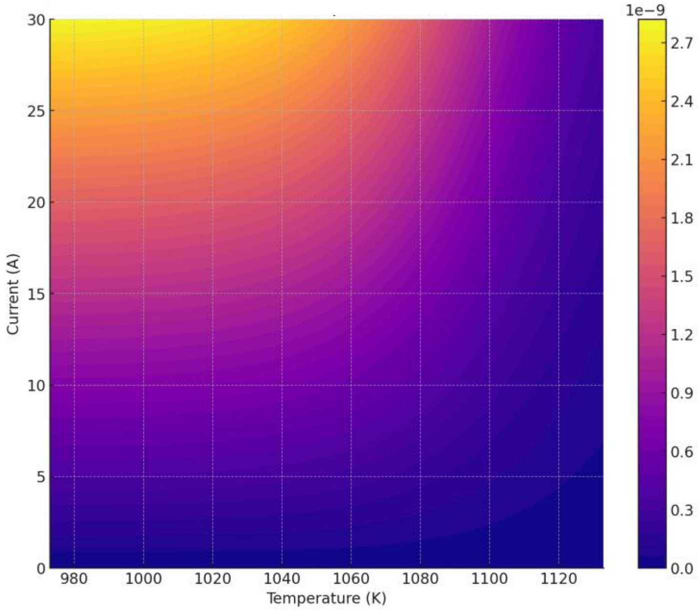
Degradation model

SOFC degradation is influenced by **operational factors** such as **temperature cycles** and **current** demand, which affect long-term performance and **lead to failure**.

Voltage degradation represents the **increase in voltage losses** due to cell ageing and suboptimal operation.

The selected experimental model* relates the rate of increase in the Ohmic resistance of the cell with its current state of operation, namely:

- Cell internal temperature
- Current
- Fuel utilization



$$\frac{dR_a}{dt} = \frac{\bar{k}_1 \mu_f + \bar{k}_2}{1 + e^{\frac{T - \bar{k}_3}{\bar{k}_4}}} \left(e^{\frac{\bar{k}_5 I}{A}} - 1 \right) \frac{R_a}{\bar{k}_0}$$

Fuel utilization

Temperature

Current

***A distributed real-time model of degradation in a solid oxide fuel cell, part I: Model characterization**
V. Zaccaria et al., 2016

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Control Objective

Nonlinear Behavior
Addresses the inherent nonlinear behavior and complexity of SOFCs by accounting for the interaction between fast electrochemical reactions and slow thermal dynamics

Dynamic tracking
Efficient electrical power load tracking and precise cell internal temperature management, while ensuring that operational constraints are met throughout varying conditions.

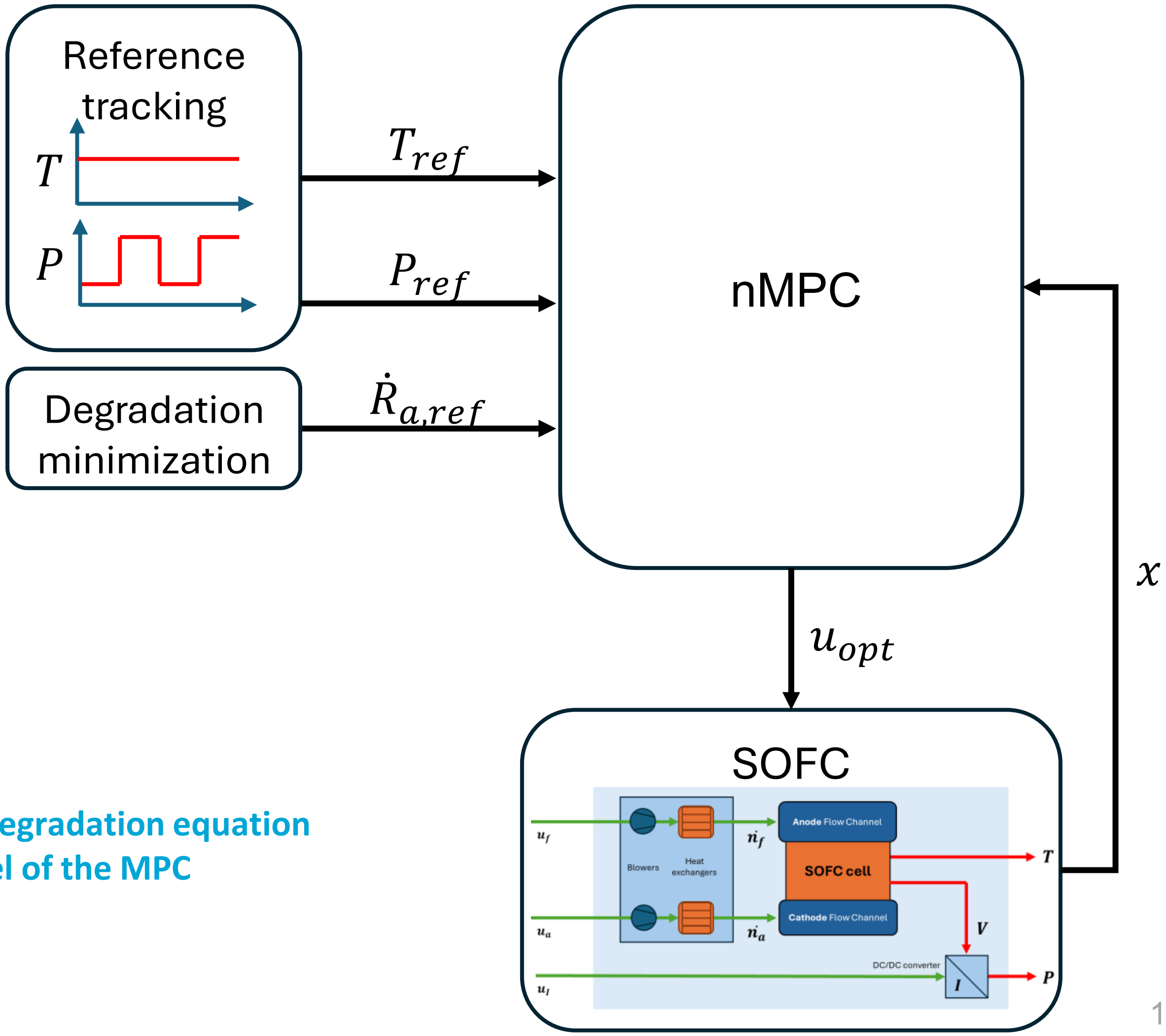
Longevity and degradation
Incorporate the degradation model to optimize system operation at specific working points, reducing degradation and enhancing the SOFC's lifespan.

Degradation-Conscious nMPC

Nonlinear Model predictive controller

- Deal with **highly nonlinear** dynamics
- **Exploit** the **ROM** of the SOFC and the experimental equation **degradation** rate
- Deal with **operational constraints**

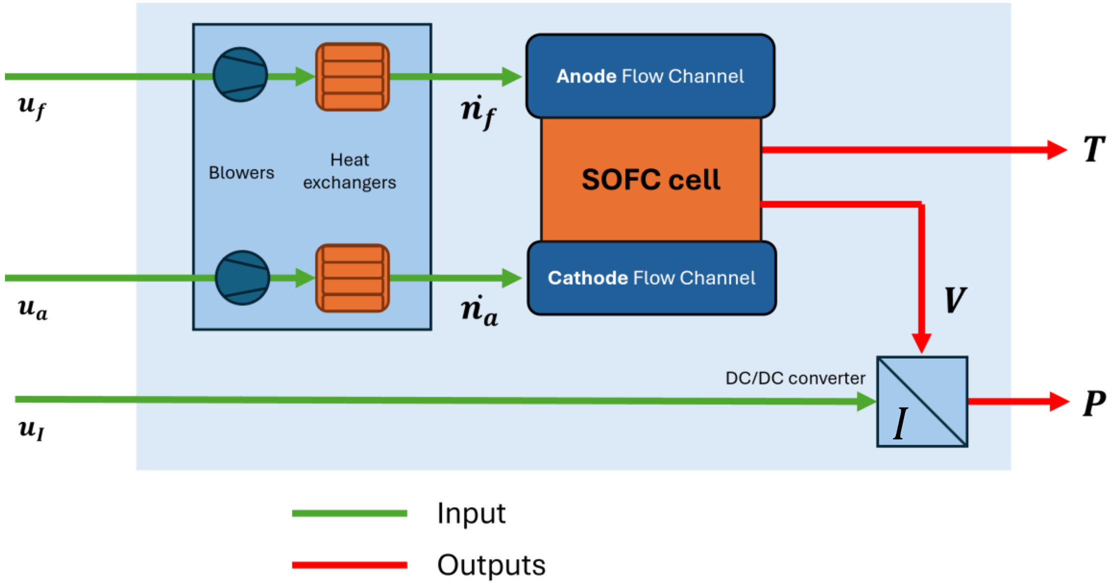
Explicitly include the degradation equation in the prediction model of the MPC



Extended State space representation

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} = \begin{bmatrix} T \\ R_a \\ n_f \\ n_a \\ I \end{bmatrix} \in \mathbb{R}^5$$

$$u = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} u_f \\ u_a \\ u_I \end{bmatrix} \in \mathbb{R}^3$$



Physical system

Extended State space representation

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} = \begin{bmatrix} T \\ R_a \\ n_f \\ n_a \\ I \end{bmatrix} \in \mathbb{R}^5$$

$$u = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} u_f \\ u_a \\ u_I \end{bmatrix} \in \mathbb{R}^3$$

$$\dot{x} = \mathcal{F}(x, u) = \begin{cases} \dot{x}_1 = \dfrac{1}{\bar{c}_p}\left(f(x) - g(x)x_5\right) \\ \dot{x}_2 = h(x)x_2 \\ \dot{x}_3 = -\dfrac{1}{\bar{\tau}_{x_3}}x_3 + \dfrac{1}{\bar{\tau}_{x_3}}u_1 \\ \dot{x}_4 = -\dfrac{1}{\bar{\tau}_{x_4}}x_4 + \dfrac{1}{\bar{\tau}_{x_4}}u_2 \\ \dot{x}_5 = -\dfrac{1}{\bar{\tau}_{x_5}}x_5 + \dfrac{1}{\bar{\tau}_{x_5}}u_3 \end{cases}$$

Enthapy Balance + Heat losses

$$\sum_{\substack{i\in\mathcal{S},\\ j\in\mathcal{F}_x}} \left(x_j\bar{K}_i h_i(\bar{T}_i) - \left(x_j\bar{K}_i + \textstyle\sum_m \bar{\nu}_{i,m} r_m\right) h_i(x_1)\right) + \bar{\lambda}(x_1 - \bar{T}_a)$$

Electrochemistry

$$-\frac{\Delta g}{2\bar{F}} + \frac{\bar{R}x_1}{2\bar{F}}\ln(Q) - \frac{x_5 x_2}{\bar{A}}$$

Voltage degradation

$$\frac{\bar{k}\,\bar{\mu}_f + \bar{k}_2}{1 + e^{\frac{x_1 - \bar{k}_3}{\bar{k}_4}}}\left(e^{\frac{\bar{k}_5 x_5}{\bar{A}}} - 1\right)\frac{1}{\bar{k}_0}$$

Low pass filters accounting for actuators dynamics

- Fuel valve
- Air valve
- DC/DC converter

Discretization

The continuous time state space model is discretized to be used by the MPC

Optimization problem

Cost Function

$$\min_{x,u} \sum_{k=0}^{N-1} \left(J_{0,k} + \|u_k\|_R^2 \right)$$

$$\begin{aligned}\text{subject to}\quad & x_{k+1} = \mathcal{F}_k(x_k, u_k) \\ & \overline{x}_{\min} \leq x_k \leq \overline{x}_{\max} \\ & \overline{u}_{\min} \leq u_k \leq \overline{u}_{\max} \\ & \overline{\Delta u}_{\min} \leq u_{k+1} - u_k \leq \overline{\Delta u}_{\max} \\ & h_k(x_k)x_{2,k} \leq \overline{\dot{R}}_{a,\max}\end{aligned}$$

Cost Function for reference tracking and degradation rate minimization

$$J_{0,k} = \|x_1 - T_{\text{ref},k}\|_Q^2 + \|g(x)x_5 - P_{\text{ref},k}\|_Q^2 + \|h(x)x_2 - \dot{R}_{a,\text{ref}}\|_Q^2$$

Temperature tracking
Minimize the difference between the actual temperature, x1, and the reference value T_{ref} (usually constant)

Power tracking
Minimize the difference between the actual electrical power output, given by the expression $g(x)x_5$, and the reference value P_{ref}

Rate of degradation minimization
The expression $h(x)x_2$, refers to the degradadation rate $\dot{x}_2$. By imposing $\dot{R}_{a,ref} = 0$ we ask our controller to minimize it value.

Limitation of the control effort

Optimization problem

Constraints

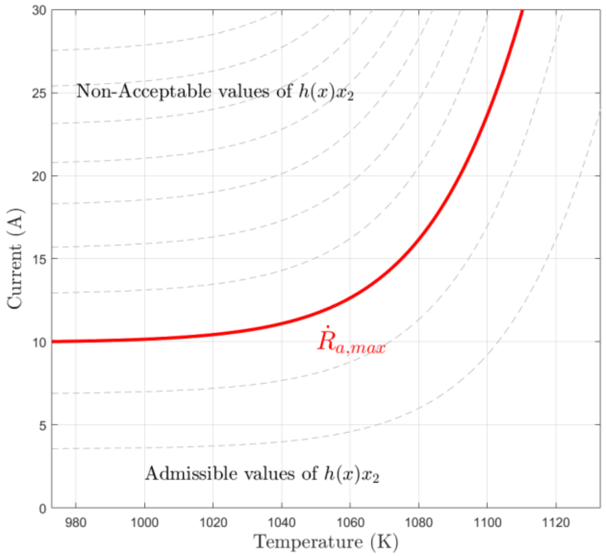
$$\min_{x,u} \quad \sum_{k=0}^{N-1} \left(J_{0,k} + \|u_k\|_R^2\right)$$

$$\text{subject to} \quad \left.\begin{aligned} & x_{k+1} = \mathcal{F}_k(x_k, u_k) \\ & \overline{x}_{\text{min}} \leq x_k \leq \overline{x}_{\text{max}} \\ & \overline{u}_{\text{min}} \leq u_k \leq \overline{u}_{\text{max}} \\ & \overline{\Delta u}_{\text{min}} \leq u_{k+1} - u_k \leq \overline{\Delta u}_{\text{max}} \end{aligned}\right\}$$

State evolution and physical operational limits constraints

$$h_k(x_k)x_{2,k} \leq \overline{\dot{R}}_{a,\text{max}} \longrightarrow$$

Maximum rate of degradation



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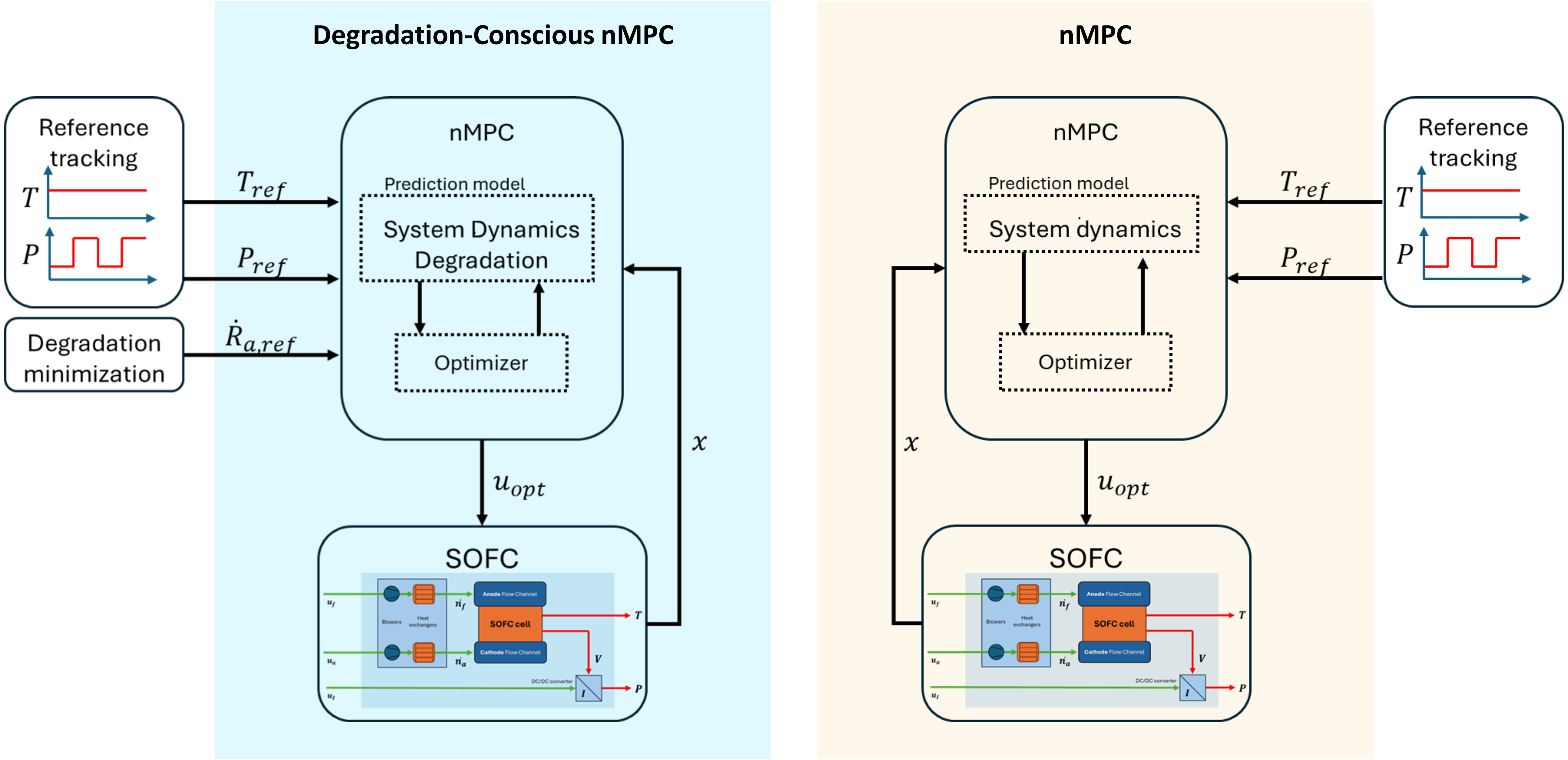
Simulation setup

	Degradation-Conscious nMPC	**nMPC**
Controller properties - Sampling Time - Moving horizon - Degradation model	 10s 30 steps ✓	 10s 3 steps ✗
Reference tracking	Temperature tracking: $T_{ref} = 1100\ K$, constant Power tracking: $P_{ref} =$ Square wave $7 - 17\ W$, 50% duty cycle over 20min	
Degradation minimization	$\dot{R}_{a,ref} = 0\ \%/h$, w.r.t. nominal condition	
Input and state constraints	Temperature, x_1 : $973 \leq x_1 \leq 1133\ K$ Fuel input, u_1 : $0 \leq u_1 \leq 5 \times 10^{-4}\ mol/s$ Air input , u_2 : $0 \leq u_2 \leq 3 \times 10^{-3}\ mol/s$ Current, u_3 : $0 \leq u_3 \leq 30\ A$	 $\lvert \Delta u_1 \rvert \leq 10\%$/min* $\lvert \Delta u_2 \rvert \leq 10\%$/min* $\lvert \Delta u_3 \rvert \leq$ 5A/min
Degradation Rate constraint	$\dot{x}_2$: $\mathrm{h}(x)x_2 \leq 0{,}45\%/h$	

*Of the Δmax flow rate, meaning that it takes 10 minutes to fully open, or fully close fuel and air valves

Simulation setup



Degradation-Conscious nMPC

Reference tracking

T

P

Degradation minimization

T_{ref}

P_{ref}

$\dot{R}_{a,ref}$

nMPC

Prediction model

System Dynamics
Degradation

Optimizer

x

u_{opt}

SOFC

nMPC

nMPC

Prediction model

System dynamics

Optimizer

Reference tracking

T

P

T_{ref}

P_{ref}

x

u_{opt}

SOFC

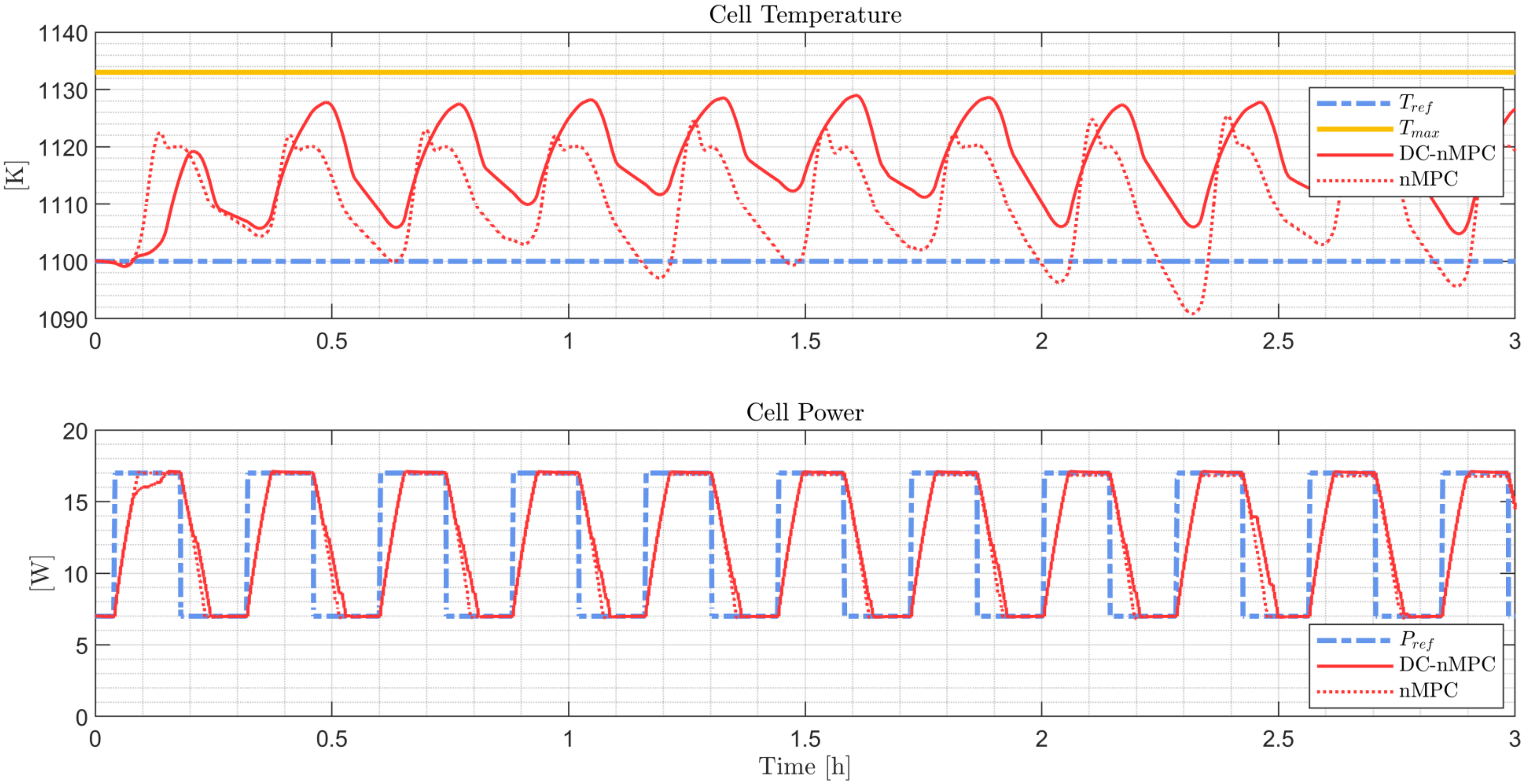
Reference Tracking

Temperature

- slightly higher value than the reference within the bounds

Power

- Precise power tracking
- Slower HI-LOW transitionc



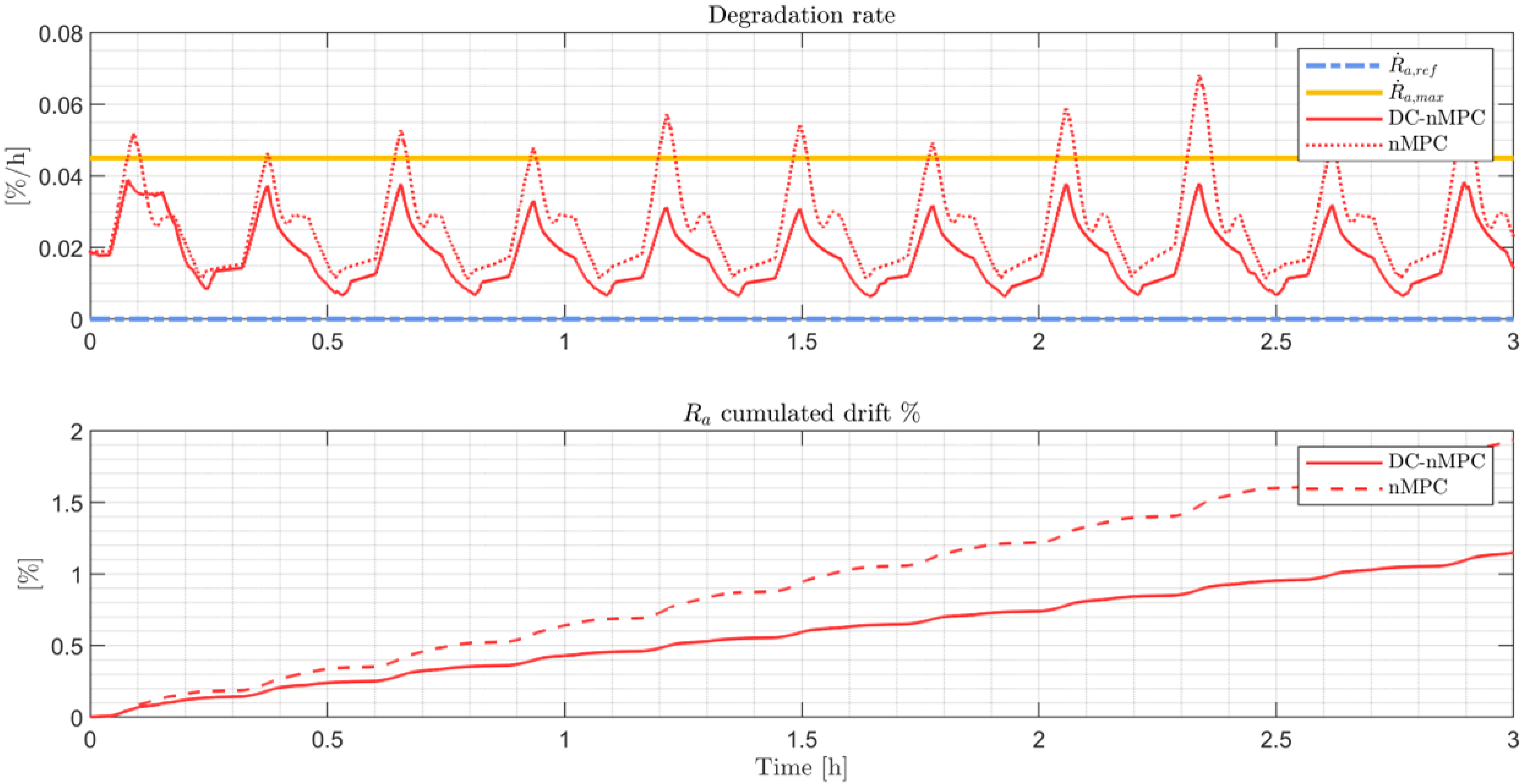
Degradation minimization

Rate of degradation

- After the warm-up o the system the degradation rate is always lower than the nMPC case
- Conservative bound

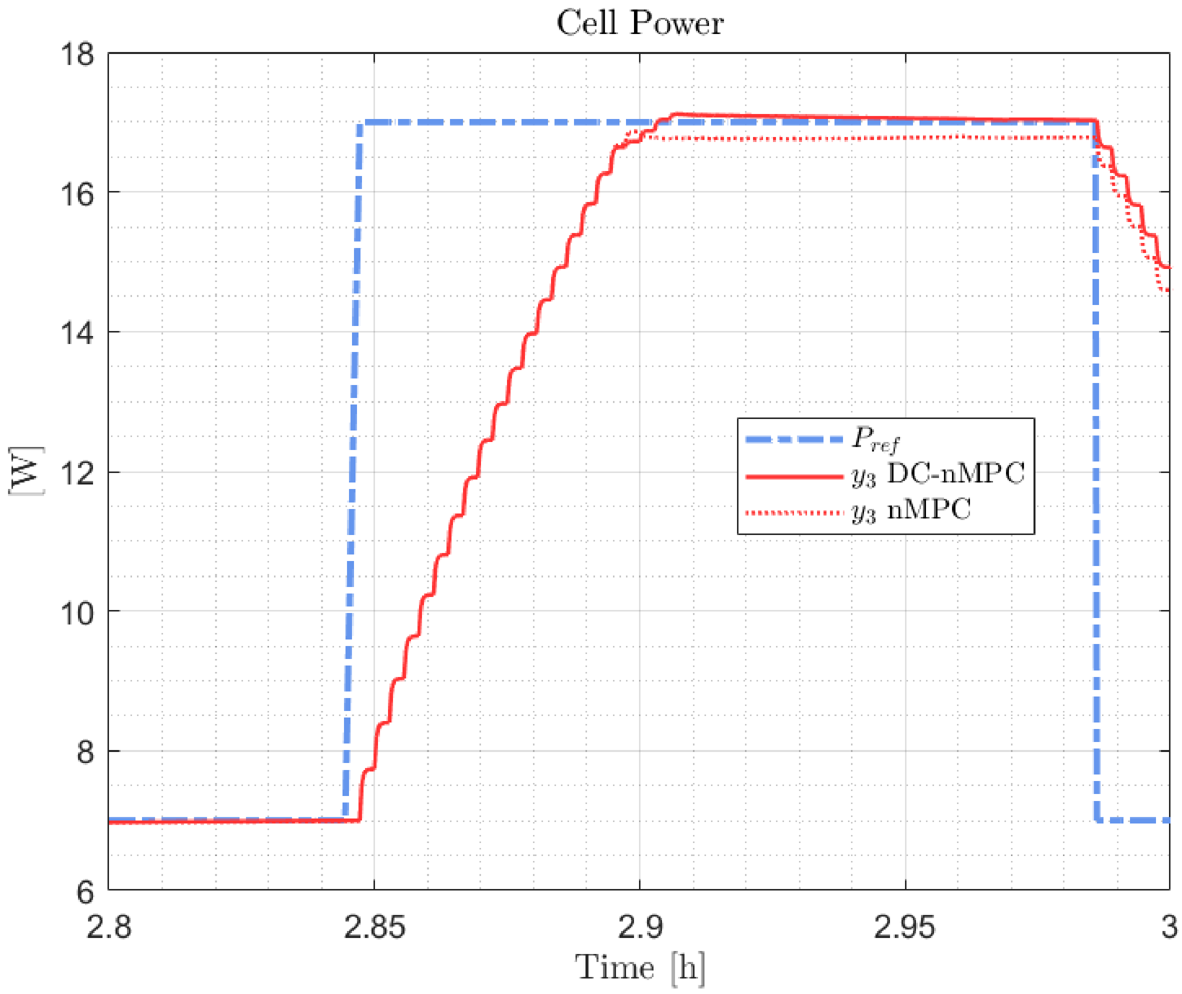
Cumulated effect

- 1% reduction at the end of simulation



Long term effect

Long term effect on the maximum reachable power



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Conclusions

We developed a **degradation-conscious controller** using **nonlinear Model Predictive Control** (nMPC) for SOFCs, addressing:

- **Nonlinearities and Constraints**: Effectively managing the intrinsic nonlinearities and operational limits of SOFCs.
- **Integrated Modeling**: Incorporating both dynamic and degradation models.
- **Operational Reliability**: Ensuring accurate reference tracking for cell temperature and power output.
- **Degradation Mitigation**: Actively reducing long-term degradation by bounding its maximum admissible value and incorporating its minimization into the cost function in real time.

Open Points

- Accounting for **model uncertainties**, particularly in the **degradation model.**
- **Extending** the approach to **ammonia-powered SOFCs** in the AmmoniaDrive project.
- Developing **fault-tolerant strategies** for enhanced reliability.

Acknowledgements

This research has been performed as part of the project AmmoniaDrive, funded by the NWO Perspectief Programme under Grant no. P20-18/14267. (c) AmmoniaDrive 2022

AMMONIA
DRIVE

This presentation has been designed using resources from Flaticon.com

Annex

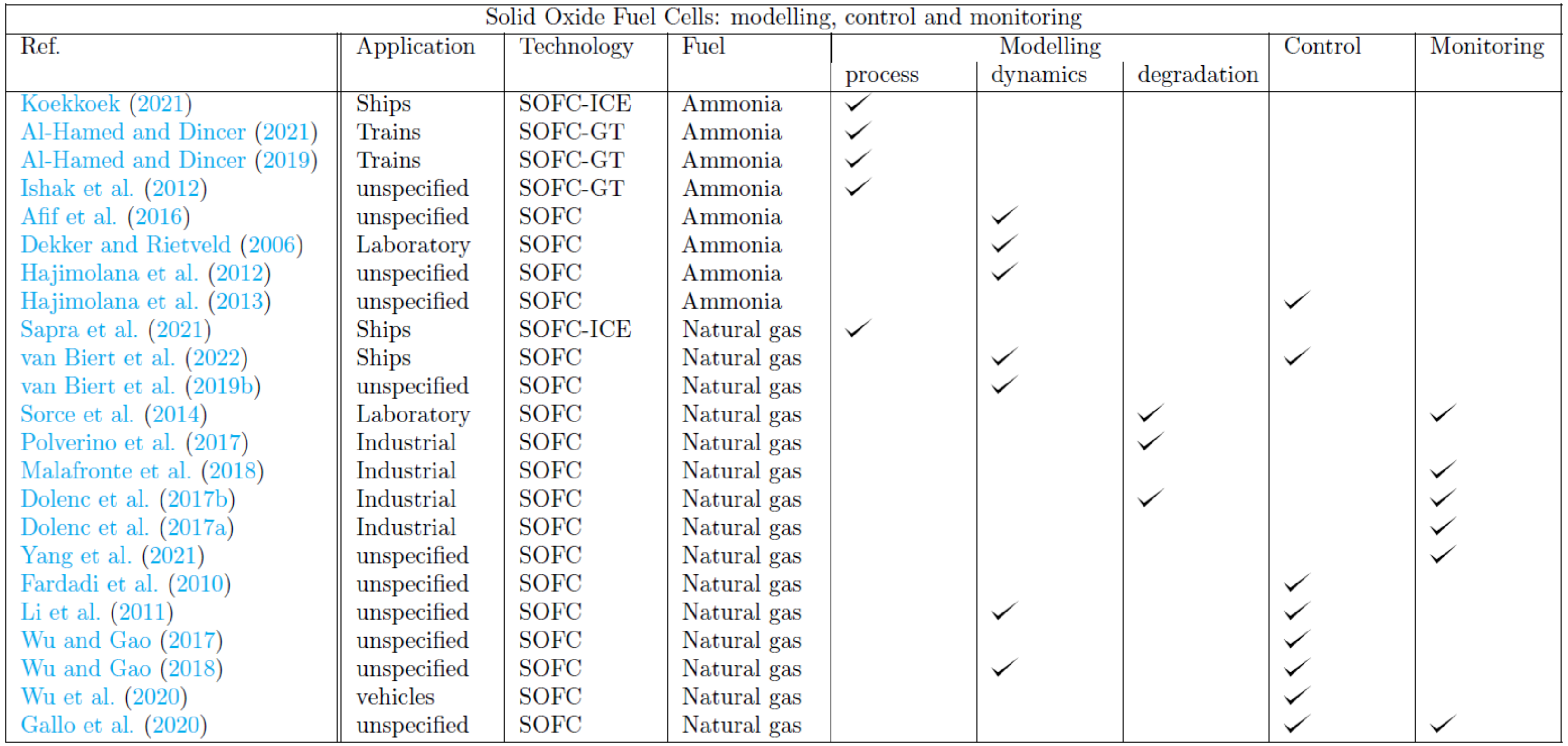
Technologies

Solid Oxide Fuel Cell

SOFCs are **electrochemical conversion devices** that produce electricity oxidizing a fuel.

Key findings

- Research on **ammonia-fueled SOFCs** is in its **early stages**, with natural gas being the primary reference fuel.
- Several **models exist** in the literature, addressing process **dynamics**, internal **thermochemistry**, and **degradation** effects.
- There are **specific control and monitoring strategies** designed for SOFCs, but these strategies are often **not combined**.



Solid Oxide Fuel Cells: modelling, control and monitoring

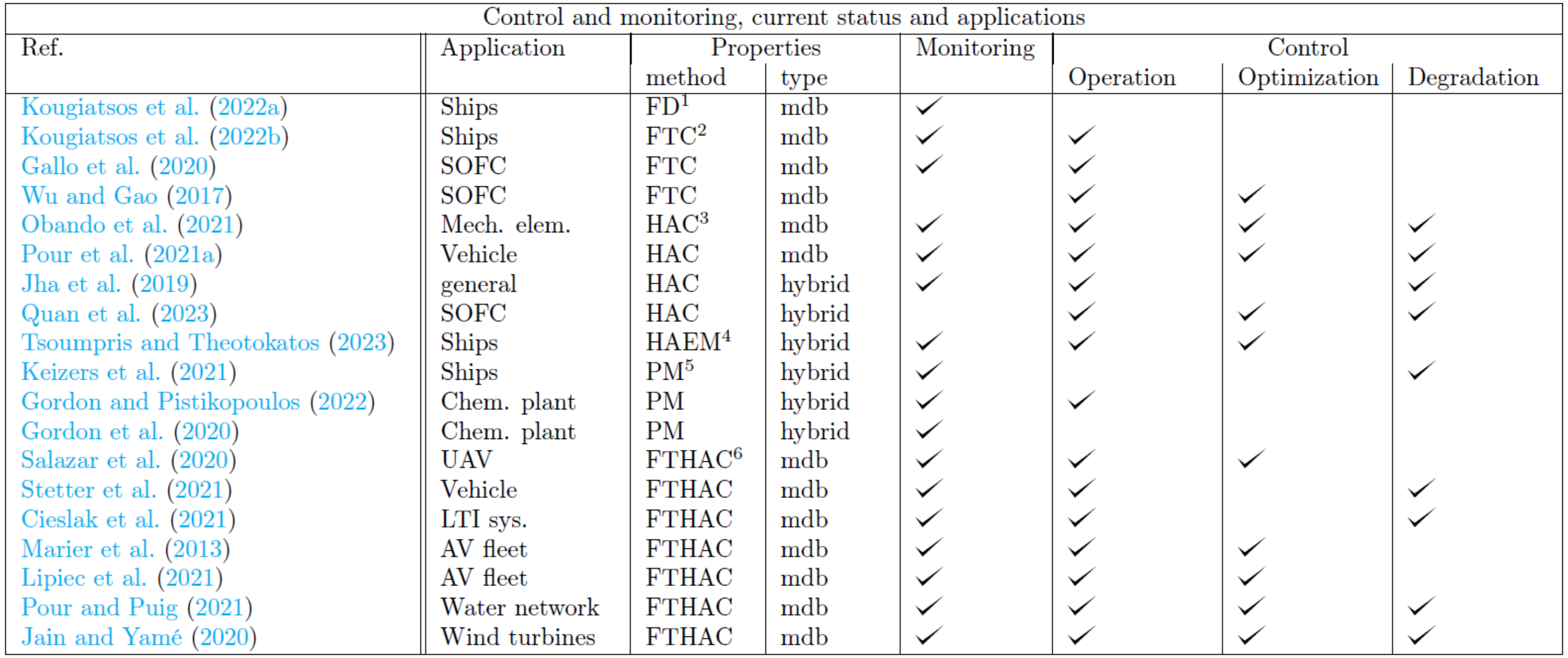
Ref.	Application	Technology	Fuel	Modelling			Control	Monitoring
				process	dynamics	degradation		
Koekkoek (2021)	Ships	SOFC-ICE	Ammonia	✓				
Al-Hamed and Dincer (2021)	Trains	SOFC-GT	Ammonia	✓				
Al-Hamed and Dincer (2019)	Trains	SOFC-GT	Ammonia	✓				
Ishak et al. (2012)	unspecified	SOFC-GT	Ammonia	✓				
Afif et al. (2016)	unspecified	SOFC	Ammonia		✓			
Dekker and Rietveld (2006)	Laboratory	SOFC	Ammonia		✓			
Hajimolana et al. (2012)	unspecified	SOFC	Ammonia		✓			
Hajimolana et al. (2013)	unspecified	SOFC	Ammonia				✓	
Sapra et al. (2021)	Ships	SOFC-ICE	Natural gas	✓				
van Biert et al. (2022)	Ships	SOFC	Natural gas		✓		✓	
van Biert et al. (2019b)	unspecified	SOFC	Natural gas		✓			
Sorce et al. (2014)	Laboratory	SOFC	Natural gas			✓		✓
Polverino et al. (2017)	Industrial	SOFC	Natural gas			✓		
Malafronte et al. (2018)	Industrial	SOFC	Natural gas					✓
Dolenc et al. (2017b)	Industrial	SOFC	Natural gas			✓		✓
Dolenc et al. (2017a)	Industrial	SOFC	Natural gas					✓
Yang et al. (2021)	unspecified	SOFC	Natural gas					✓
Fardadi et al. (2010)	unspecified	SOFC	Natural gas				✓	
Li et al. (2011)	unspecified	SOFC	Natural gas		✓		✓	
Wu and Gao (2017)	unspecified	SOFC	Natural gas				✓	
Wu and Gao (2018)	unspecified	SOFC	Natural gas		✓		✓	
Wu et al. (2020)	vehicles	SOFC	Natural gas				✓	
Gallo et al. (2020)	unspecified	SOFC	Natural gas				✓	✓

Combination of control and monitoring

Combining **fault mitigation** with **real-time health assessments** can **enhance reliability** and **performance** across various engineering applications.

Key findings

- **Predominantly model-based techniques** with some hybrid approaches integrating data-driven processes
- These strategies are **implemented** across a **diverse range** of engineering systems. Most of them are **application specific**.



Control and monitoring, current status and applications

Ref.	Application	Properties method	Properties type	Monitoring	Control Operation	Control Optimization	Control Degradation
Kougiatsos et al. (2022a)	Ships	FD[1]	mdb	✓			
Kougiatsos et al. (2022b)	Ships	FTC[2]	mdb	✓	✓		
Gallo et al. (2020)	SOFC	FTC	mdb	✓	✓		
Wu and Gao (2017)	SOFC	FTC	mdb		✓	✓	
Obando et al. (2021)	Mech. elem.	HAC[3]	mdb	✓	✓	✓	✓
Pour et al. (2021a)	Vehicle	HAC	mdb	✓	✓	✓	✓
Jha et al. (2019)	general	HAC	hybrid	✓	✓		✓
Quan et al. (2023)	SOFC	HAC	hybrid		✓	✓	✓
Tsoumpris and Theotokatos (2023)	Ships	HAEM[4]	hybrid	✓	✓	✓	
Keizers et al. (2021)	Ships	PM[5]	hybrid	✓			✓
Gordon and Pistikopoulos (2022)	Chem. plant	PM	hybrid	✓	✓		
Gordon et al. (2020)	Chem. plant	PM	hybrid	✓			
Salazar et al. (2020)	UAV	FTHAC[6]	mdb	✓	✓	✓	
Stetter et al. (2021)	Vehicle	FTHAC	mdb	✓	✓		✓
Cieslak et al. (2021)	LTI sys.	FTHAC	mdb	✓	✓		✓
Marier et al. (2013)	AV fleet	FTHAC	mdb	✓	✓	✓	
Lipiec et al. (2021)	AV fleet	FTHAC	mdb	✓	✓	✓	
Pour and Puig (2021)	Water network	FTHAC	mdb	✓	✓	✓	✓
Jain and Yamé (2020)	Wind turbines	FTHAC	mdb	✓	✓	✓	✓

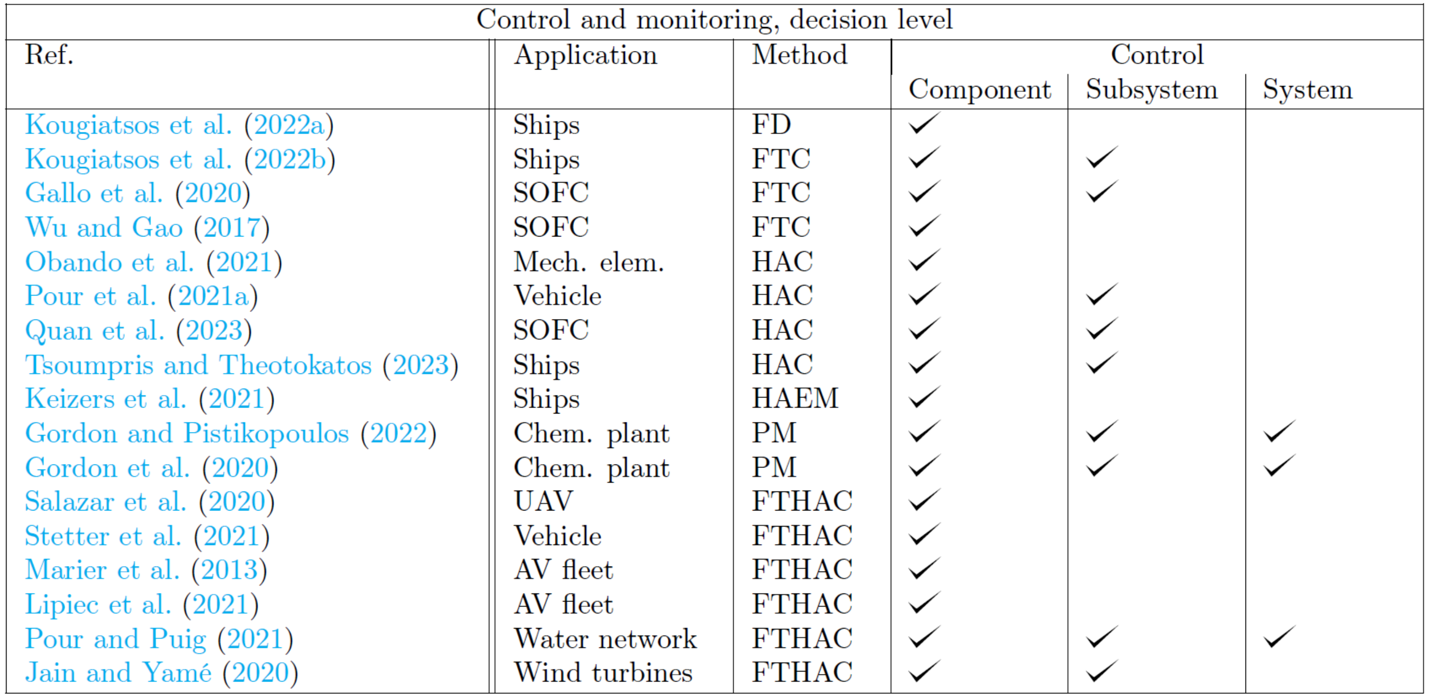
FD: Fault Detection, **FTC**: Fault Tolerant Control, **HAC**: Health Aware Control, **HAEM**: Health Aware Energy Management, **PM**: Predictive Maintenance, **FTHAC**: Fault tolerant Health Aware Control.

Combination of control and monitoring

Connection of the selected studies with the control decision levels of the Ammoniadrive ship.

Key findings

- **Studies typically address component-level complexities**, with several methods extending to the subsystem level.
- Few works extend their strategies to the **system level**, often applied to **simplified networked systems**



Control and monitoring, decision level

Ref.	Application	Method	Control		
			Component	Subsystem	System
Kougiatsos et al. (2022a)	Ships	FD	✓		
Kougiatsos et al. (2022b)	Ships	FTC	✓	✓	
Gallo et al. (2020)	SOFC	FTC	✓	✓	
Wu and Gao (2017)	SOFC	FTC	✓		
Obando et al. (2021)	Mech. elem.	HAC	✓		
Pour et al. (2021a)	Vehicle	HAC	✓	✓	
Quan et al. (2023)	SOFC	HAC	✓	✓	
Tsoumpris and Theotokatos (2023)	Ships	HAC	✓	✓	
Keizers et al. (2021)	Ships	HAEM	✓		
Gordon and Pistikopoulos (2022)	Chem. plant	PM	✓	✓	✓
Gordon et al. (2020)	Chem. plant	PM	✓	✓	✓
Salazar et al. (2020)	UAV	FTHAC	✓		
Stetter et al. (2021)	Vehicle	FTHAC	✓		
Marier et al. (2013)	AV fleet	FTHAC	✓		
Lipiec et al. (2021)	AV fleet	FTHAC	✓		
Pour and Puig (2021)	Water network	FTHAC	✓	✓	✓
Jain and Yamé (2020)	Wind turbines	FTHAC	✓	✓	

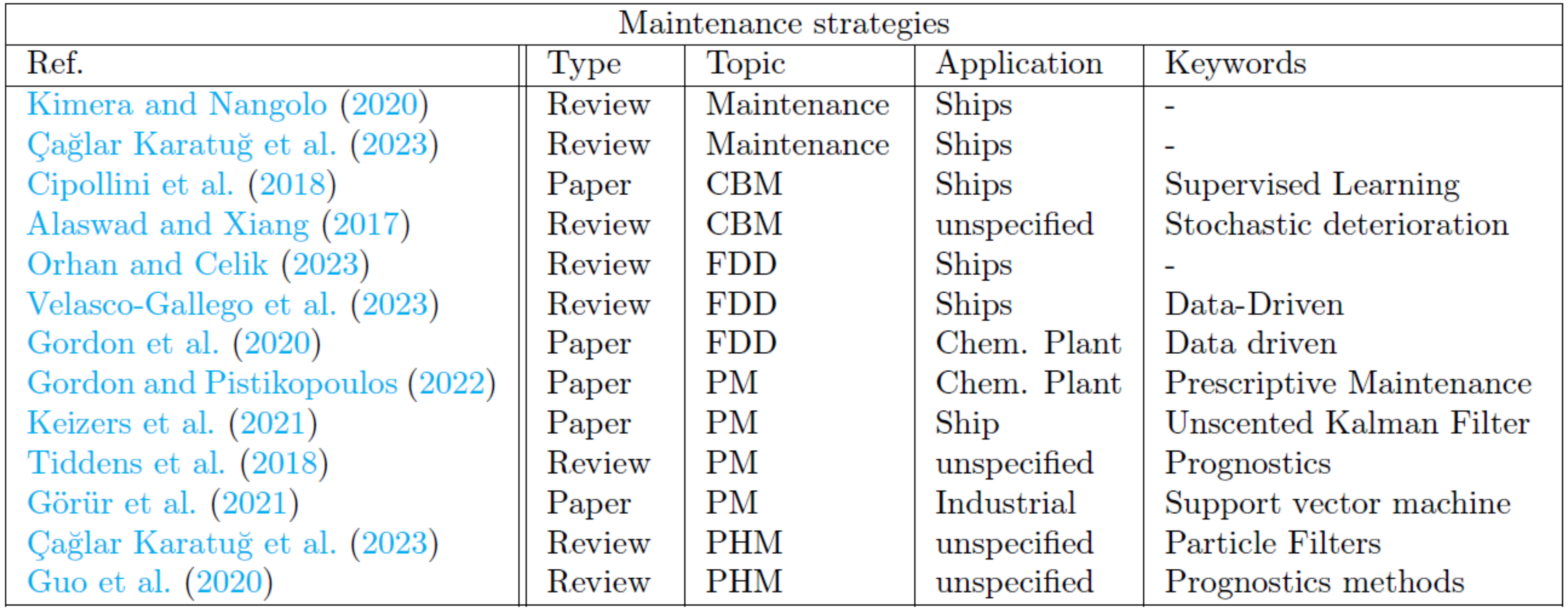
Decision level in the selected control and monitoring studies

Integration of maintenance planning

Smart control enhances system operation and can reduce component wear and operative costs, but **maintenance remains essential**.

Key findings

- The topic spans from **maintenance tasks** to smart **algorithms** and **strategies** that
  - **Assess the necessity** of maintenance
  - **Optimize the timing** and level of **proactivity** in scheduling maintenance activities
- **The concept of Remaining Useful Life (RUL) connects maintenance and control**, guiding decisions to maximize system lifespan.



Maintenance strategies

Ref.	Type	Topic	Application	Keywords
Kimera and Nangolo (2020)	Review	Maintenance	Ships	-
Çağlar Karatuğ et al. (2023)	Review	Maintenance	Ships	-
Cipollini et al. (2018)	Paper	CBM	Ships	Supervised Learning
Alaswad and Xiang (2017)	Review	CBM	unspecified	Stochastic deterioration
Orhan and Celik (2023)	Review	FDD	Ships	-
Velasco-Gallego et al. (2023)	Review	FDD	Ships	Data-Driven
Gordon et al. (2020)	Paper	FDD	Chem. Plant	Data driven
Gordon and Pistikopoulos (2022)	Paper	PM	Chem. Plant	Prescriptive Maintenance
Keizers et al. (2021)	Paper	PM	Ship	Unscented Kalman Filter
Tiddens et al. (2018)	Review	PM	unspecified	Prognostics
Görür et al. (2021)	Paper	PM	Industrial	Support vector machine
Çağlar Karatuğ et al. (2023)	Review	PHM	unspecified	Particle Filters
Guo et al. (2020)	Review	PHM	unspecified	Prognostics methods

Combining monitoring strategies and control algorithms

Main Gaps

Technologies SOFC (and ICE)

- Models for **ammonia fuelled SOFCs*** are not yet well-developed
- Significant gap in **integrating control and monitoring** activities on SOFCs

Combination of control and monitoring

- Existing strategies for combining control and monitoring are **largely application-dependent**
- **Strategies exist for individual components**, comprehensive solutions for **large-scale, interconnected systems**, are **lacking**

Integration of maintenance planning

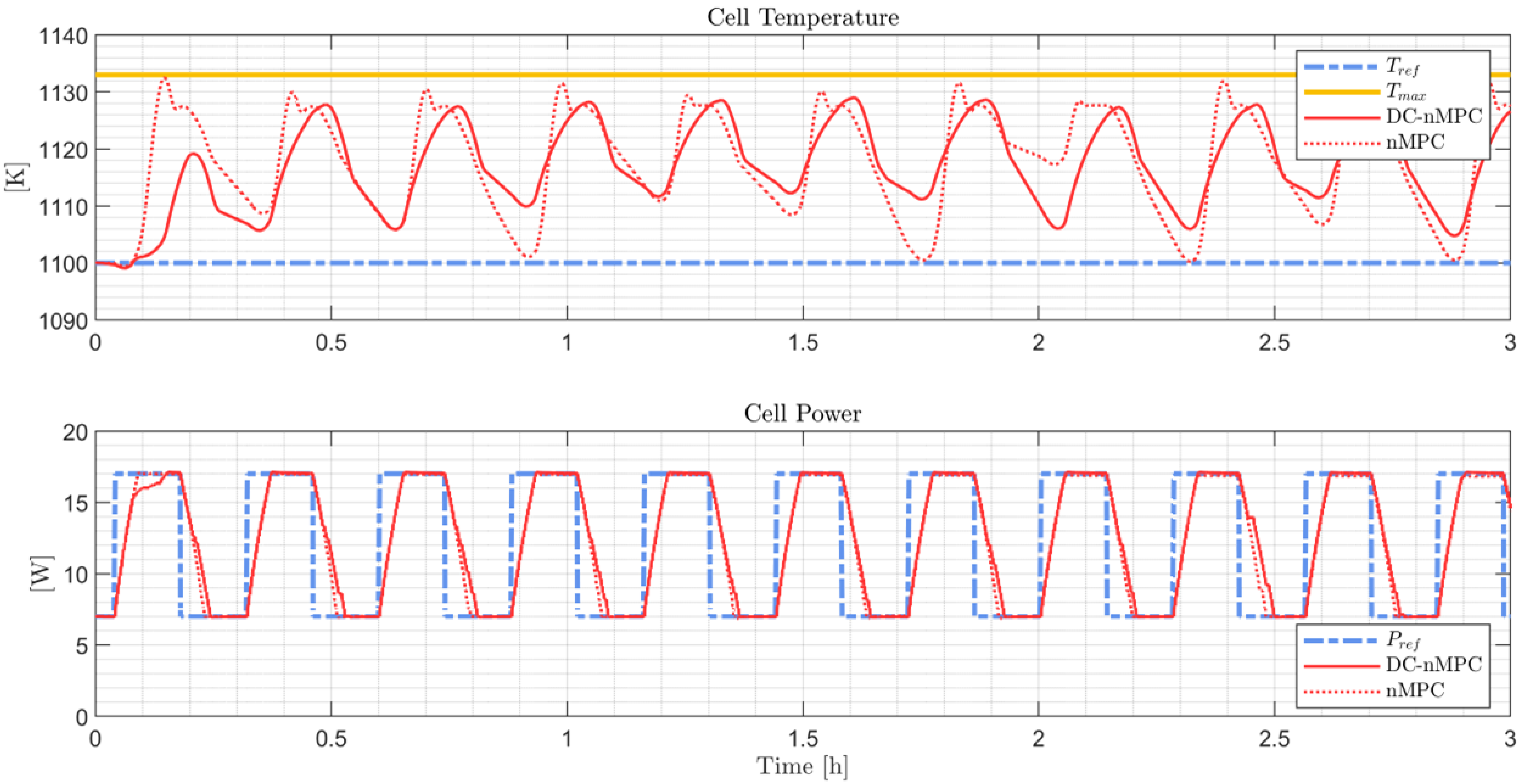
- Current approaches do not integrate maintenance planning with real-time control strategies that **consider the system's RUL as a dynamic state influenced by operational profiles and conditions**

***Also Ammonia fuelled ICEs** models are under development, currently **no control-oriented formulation** available

Reference Tracking

Temperature

- nMPC temperature reference at 1120K



Degradation minimization

Rate of degradation

- Working at higher temperature reduces the rate of degradation of the nMPC case

Cumulated effect

- 0.5% reduction at the end of simulation