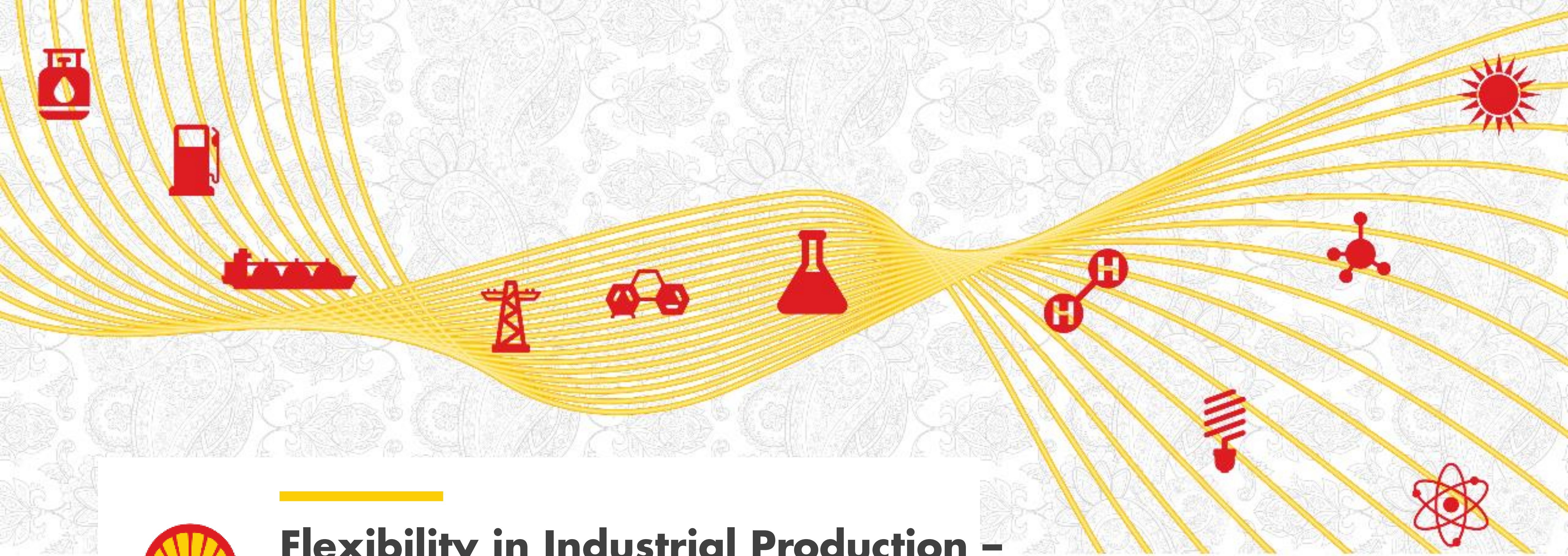

Flexibility in Industrial Production – A view on status and prospects

Elizabeth Endler
Shell International Exploration and Production Inc.
Program Lead, Advanced Energy Storage
18 March 2020
Presentation for ESIG Spring Technical Workshop, Tucson, AZ

Definitions & cautionary note

The companies in which Royal Dutch Shell plc directly and indirectly owns investments are separate legal entities. In this presentation “Shell”, “Shell group” and “Royal Dutch Shell” are sometimes used for convenience where references are made to Royal Dutch Shell plc and its subsidiaries in general. Likewise, the words “we”, “us” and “our” are also used to refer to subsidiaries in general or to those who work for them. These expressions are also used where no useful purpose is served by identifying the particular company or companies. ‘‘Subsidiaries’’, “Shell subsidiaries” and “Shell companies” as used in this presentation refer to companies over which Royal Dutch Shell plc either directly or indirectly has control. Entities and unincorporated arrangements over which Shell has joint control are generally referred to “joint ventures” and “joint operations” respectively. Entities over which Shell has significant influence but neither control nor joint control are referred to as “associates”. The term “Shell interest” is used for convenience to indicate the direct and/or indirect ownership interest held by Shell in a venture, partnership or company, after exclusion of all third-party interest.

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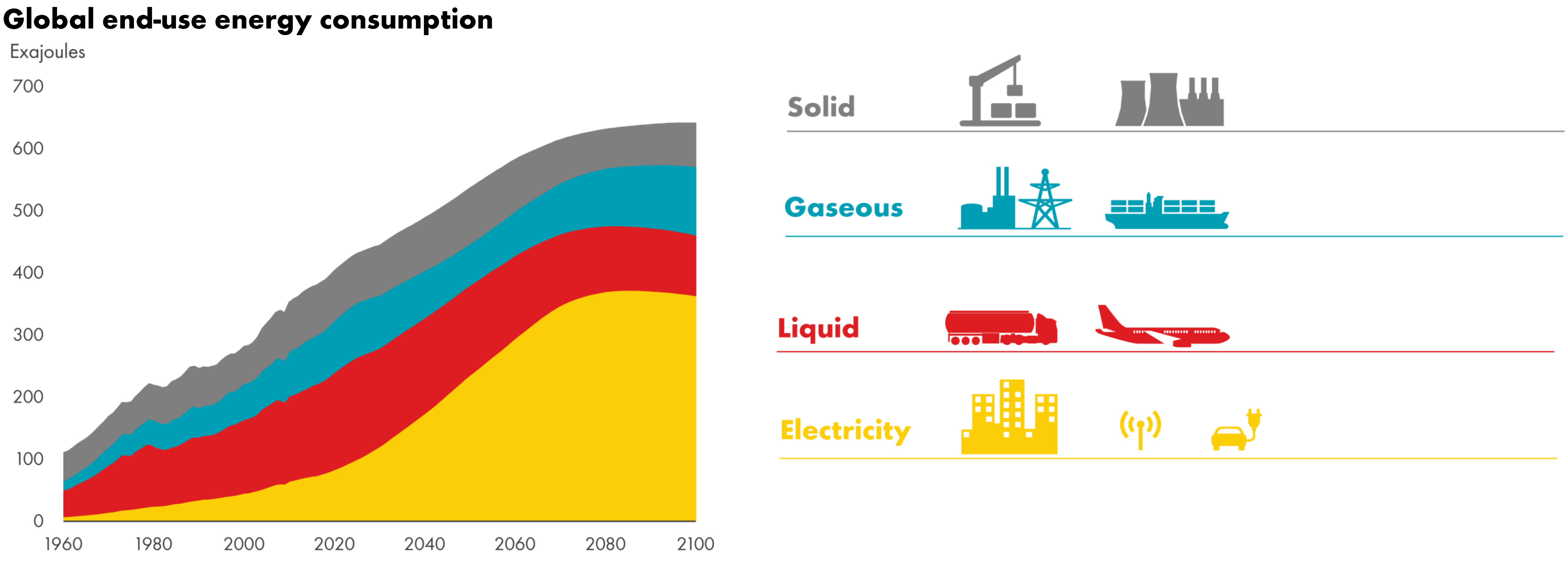
Energy outlook

Changes in consumer patterns drive a shift in the primary energy mix



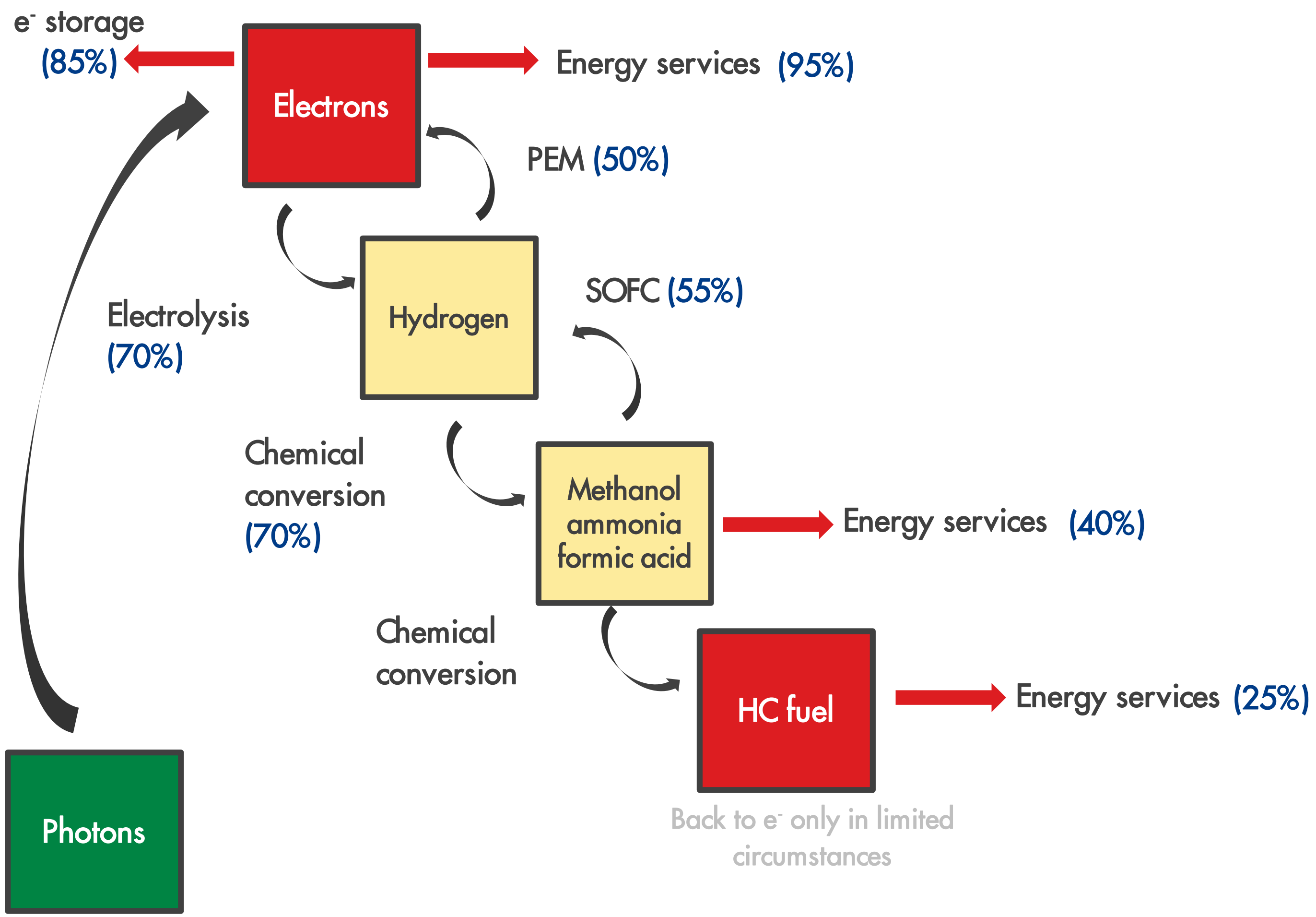
More people

More prosperity

Lower carbon

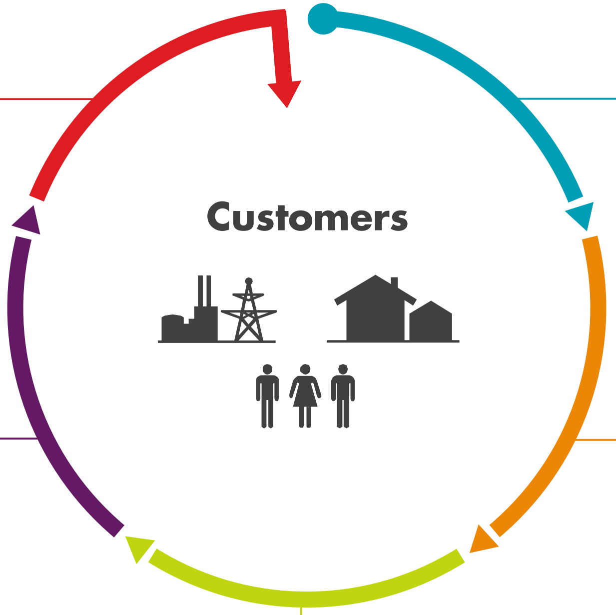
Electricity: high quality energy

Significant reduction in primary energy demand to deliver equivalent services



The lower the conversion process efficiencies for each step, the more advantaged "electric-only" pathways are on a primary energy basis

Shell business overview



01 Exploration

- Exploring for oil and gas: offshore
- Exploring for oil and gas: onshore

02 Development and extraction

- Developing fields
- Producing oil and gas

03 Manufacturing and energy production

- Upgrading bitumen
- Refining oil into fuels and lubricants
- Converting gas into liquid products (GTL)
- Producing petrochemicals
- Producing biofuels
- Generating power

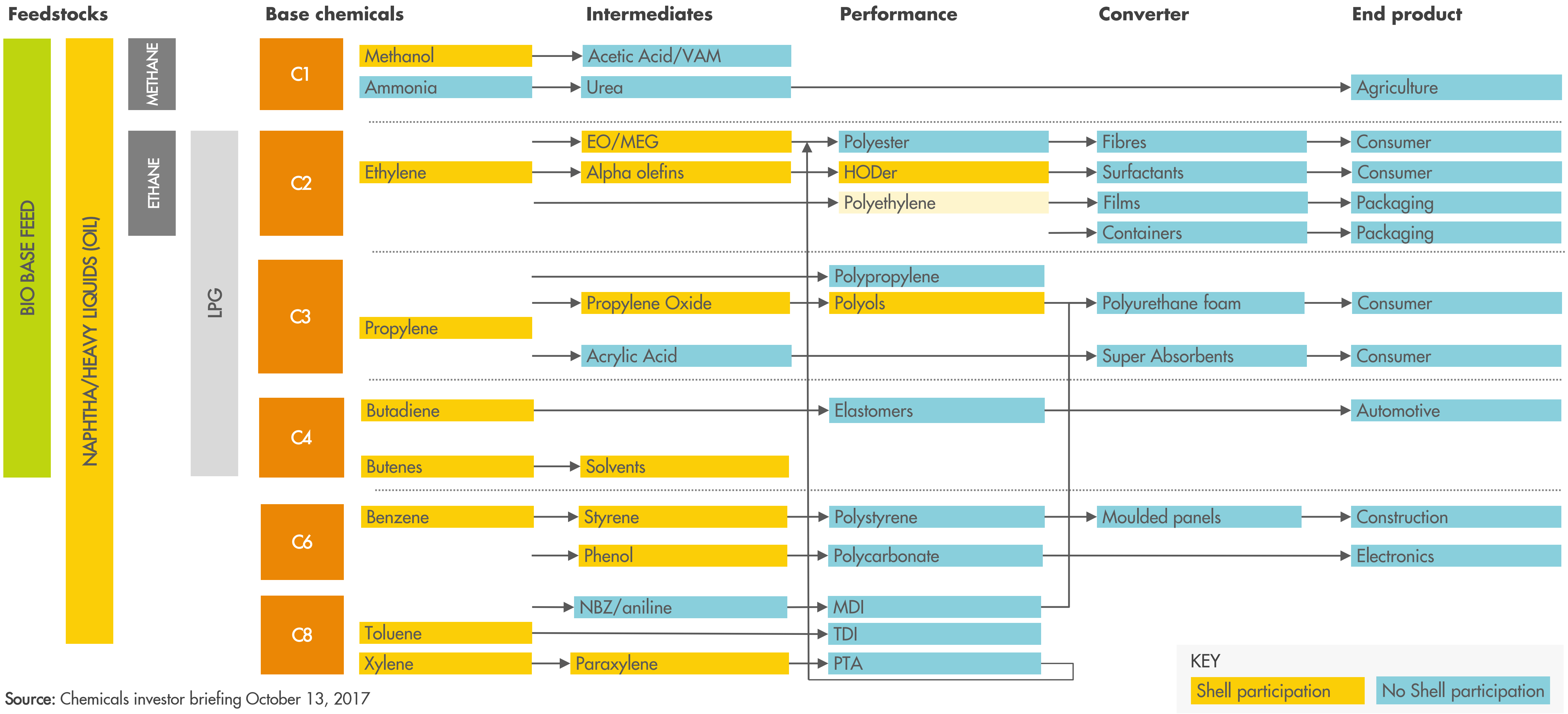
04 Transport and trading

- Liquefying gas by cooling (LNG)
- Shipping and trading
- Regasifying (LNG)
- Supply and distribution

05 Sales and marketing

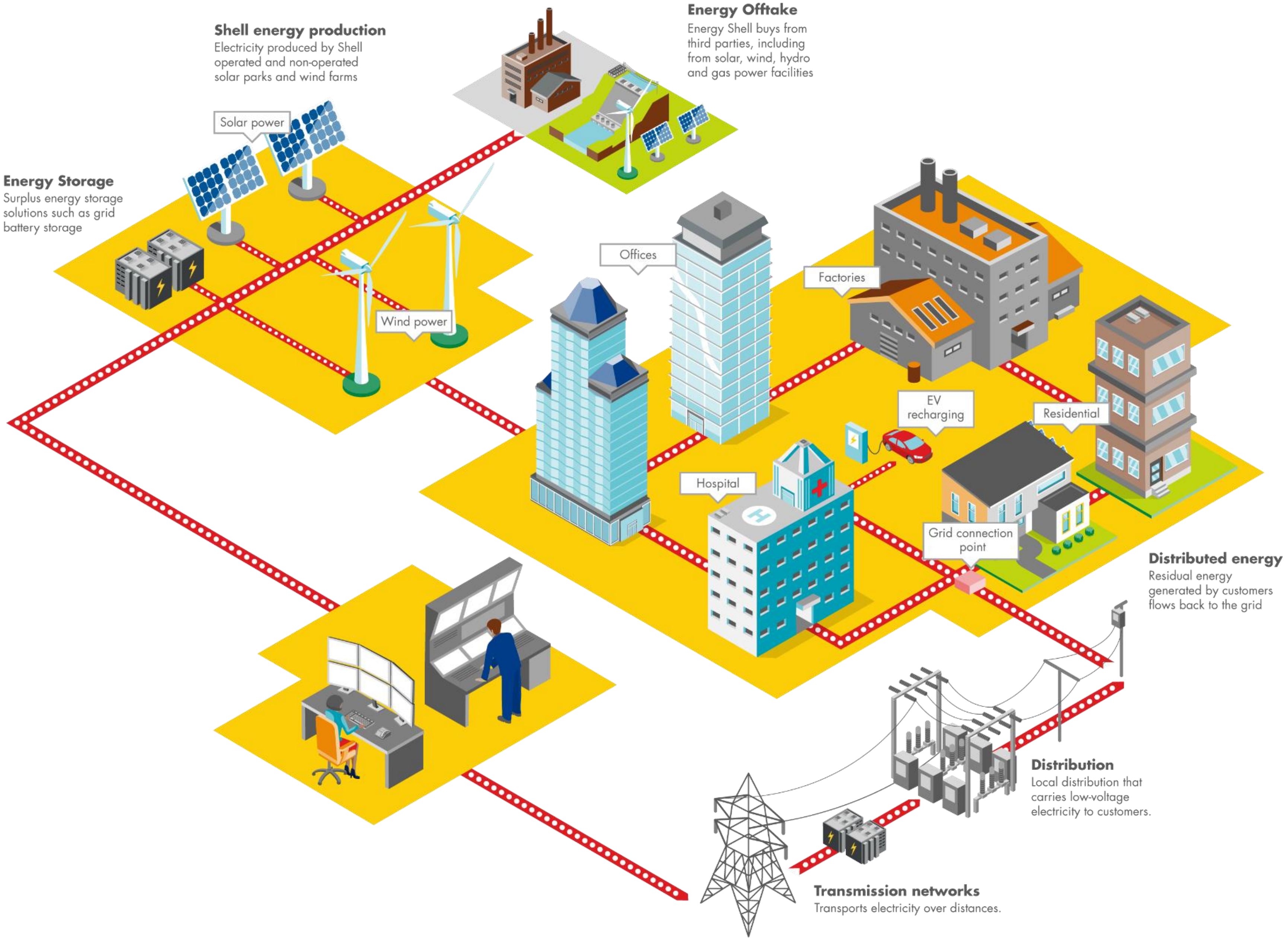
- Retail
- Lubricants
- Aviation
- Power

Chemicals value chains



Source: Chemicals investor briefing October 13, 2017

Shell and the integrated power system



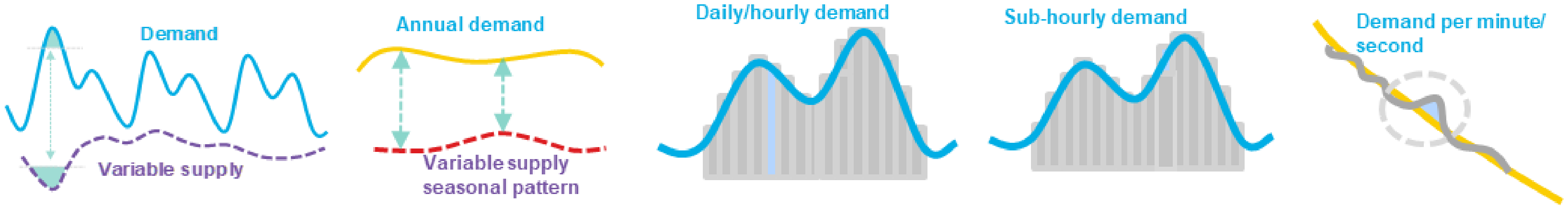
Investments and acquisitions

- Limejump, UK, 2019
- sonnen, Germany, 2019
- Greenlots, USA, 2019
- First Utility, UK, 2018 (Shell Energy Retail)
- GI Energy, USA, 2018
- Borssele 3 and 4, Netherlands, 2018
- Silicon Ranch, USA, 2018
- Cleantech Solar, Singapore, 2018
- NewMotion, UK and Europe, 2017
- Shell Recharge, UK, 2017
- MP2 Energy, USA, 2017
- WonderBill, UK, 2015

The grid requires flexibility of different types at different timescales

Manufacturing processes have analogous planning, scheduling, optimization, & control timescales

Operational timescale	Generation and transmission capacity (years before)	Long to mid-term scheduling (seasonal & weekly)	Day-ahead scheduling (one day before)	Intraday (during the day)	Balancing (≤15 minutes or/and real time)
Flexibility needs	Need for flexibility adequacy planning - to prepare for extreme events.	Need for flexibility to address seasonal behavior of variable generation & demand.	Daily/hourly scheduling plan for the next day/hourly demand.	Load following to meet sub-hourly demand in real-time.	Maintain system frequency in real-time - remediate frequency deviations caused by forecasting errors and contingency events

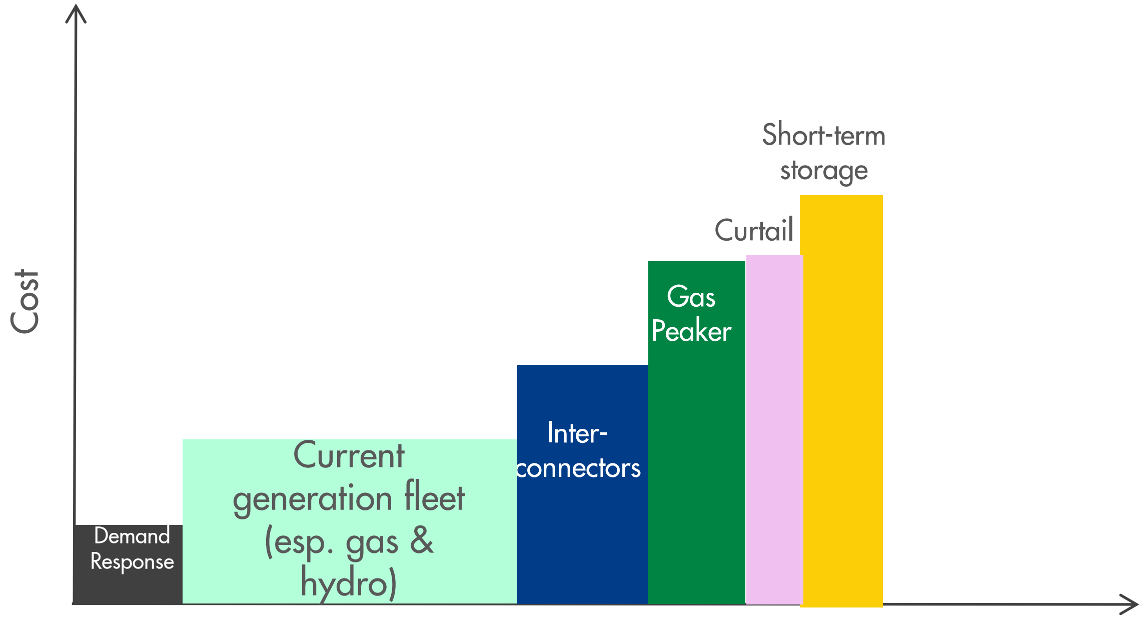


IRENA defines flexibility as "the capability of a power system to cope with the variability and uncertainty that solar and wind energy introduce at different time scales, from the very short to the long term, minimising curtailment of power from these variable renewable energy (VRE) sources and reliably supplying all customer energy demand" (IRENA, 2018a).

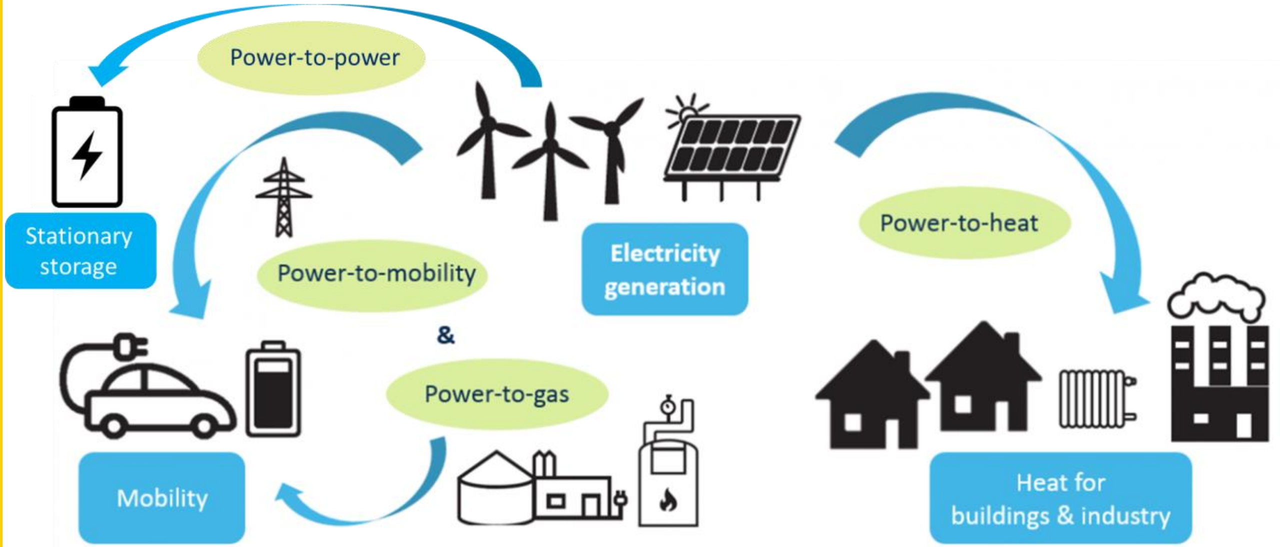
Source: Bloomberg NEF, NREL. IRENA (2019), Demand-side flexibility for power sector transformation, International Renewable Energy Agency, Abu Dhabi..

Flexibility can be provided in multiple ways by multiple sources

Conceptual representation of today: power sector only



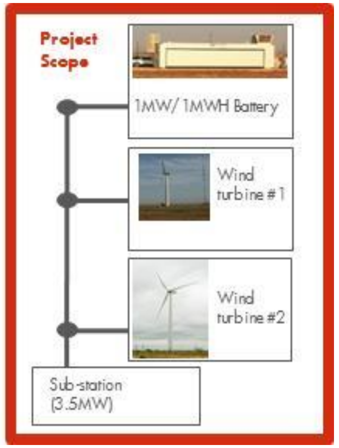
Potential future: Sector Coupling



Source: Appunn K., "Sector coupling – Shaping an integrated renewable energy system", Clean Energy Wire, 25 April 2018. IRENA (2019), *Demand-side flexibility for power sector transformation;* Shell analysis

Shell's Approach: R&D Examples of Stationary Energy Storage

Using storage at multiple scales for flexibility



Wind Integration in West Texas

- Observed performance of MW-scale wind + lithium-ion battery for key applications
- Multiple applications of storage are technically feasible, which enables increased revenue capture and improved economics

Microgrid at Shell Technology Center Houston

- Commercial & industrial scale
- Solar PV, batteries, gas generator, and load bank
- Coupled to building loads

EcoGenie House (The Hague, NL)

- "Living Laboratory" at residential scale
- Low-carbon electricity and heating technologies
  - Solar PV (rooftop), energy storage (batteries & thermal), heat pumps, boilers

Industrial electrification is not new

…but the paradigms for future processes could be

"Industrial Electrification & New Technology" (EPRI, 1983)

I. Leslie Harry

Electric Power Research Institute
Palo Alto, California

ABSTRACT

Today, I'd like to discuss the subjects of industrial electrification and new technology. I hope, that by the end of my presentation, you will have answers to the following questions of:

What is Industrial Electrification?

Why is it of significance or value?

Where and how is it being utilized?

What are its economic implications?, and

What is the status of US/EPRI activities?

Finally, I'll end by making a few comments on why industrial electrification might be of particular significance to the Middle Eastern Countries.

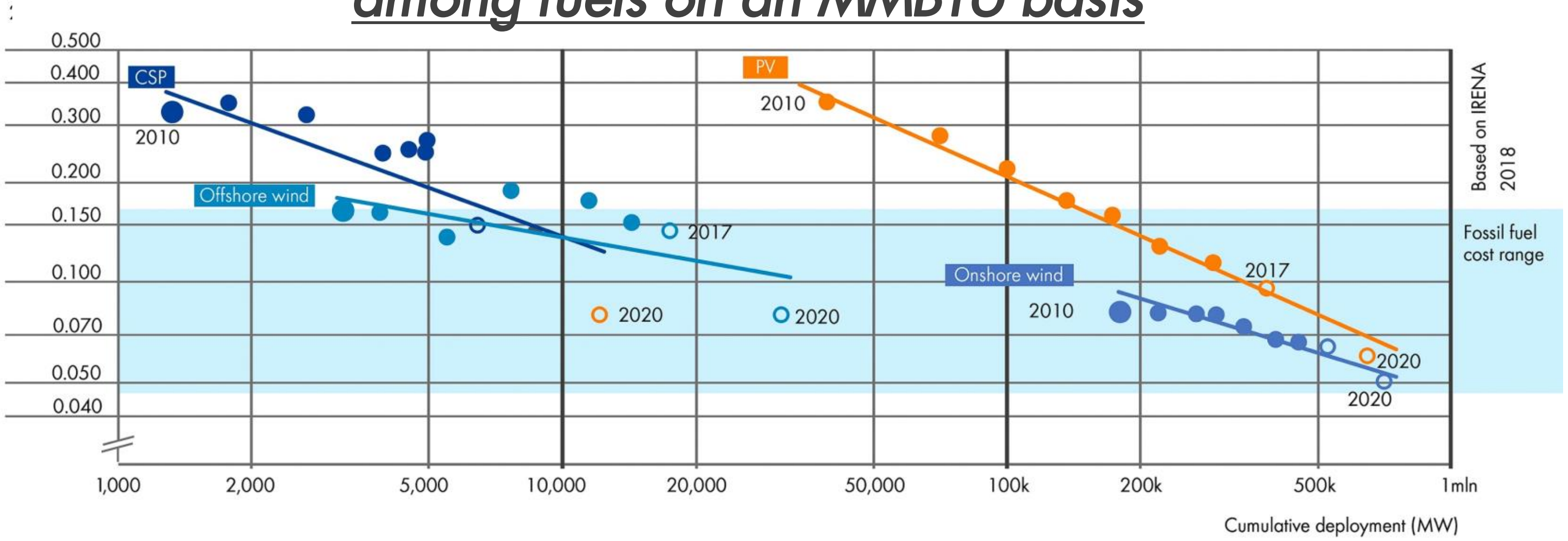
KEYWORDS

Electrification, new technology, industrial electrification, fuel switching, electric steelmaking, primary energy source.

INTRODUCTION

Industrial electrification implies substitution of electricity as the primary energy source in an industrial process. This concept sounds relatively simple, particularly in light of the economic reality of the value of petroleum when defined as a "scarce resource". However, why would someone, rather some company or industry, want to substitute electricity -- which now costs industrial customers about $15 per million Btu -- for oil (costing $8) or gas (at about $4)? Well, the answer to this paradox -- and the reason why electrification of industry is fast becoming a concept of

Price declines for electricity begin to close historical gap among fuels on an MMBTU basis



Cost curves are based on global weighted averages. Fossil fuel-fired power generation costs are shown for G20 countries in 2017 and vary between USD 0.05 and USD 0.17/kWh.

Notional power cost thresholds for large-scale electrification

Cement: $25-50/MWh

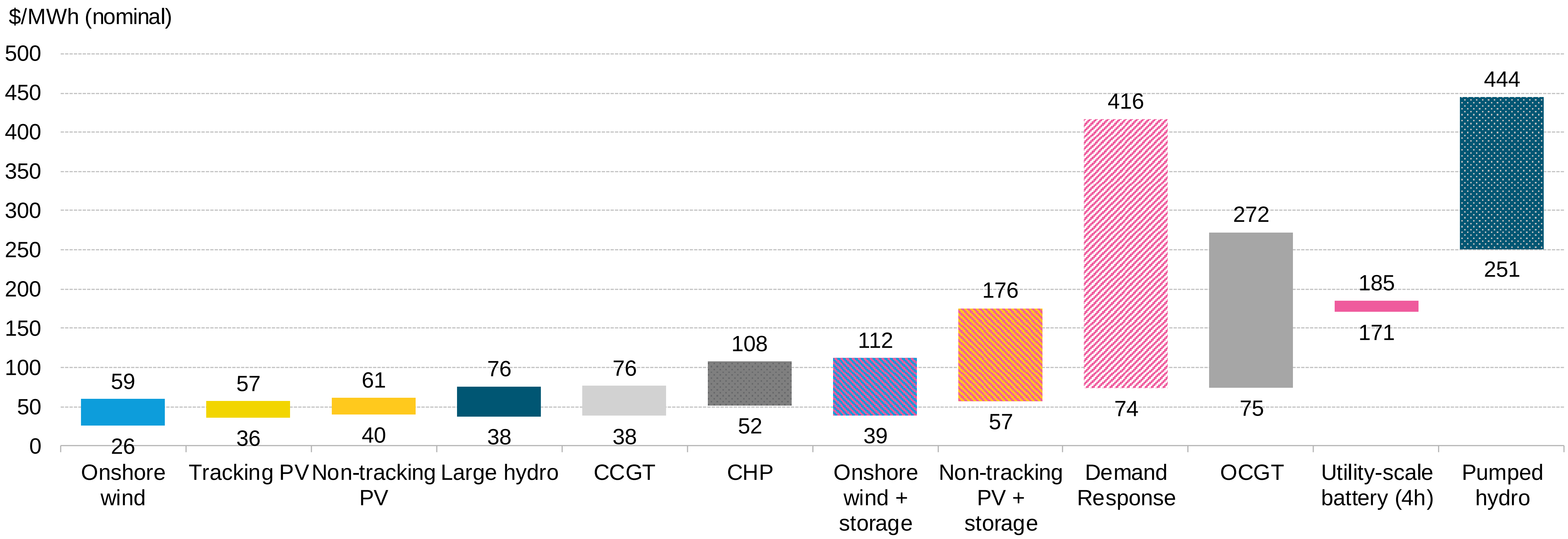
Steel (via H_2): $25-40/MWh

Ethylene: $15-$25/MWh

Sources: https://doi.org/10.1016/B978-0-08-031141-8.50020-3; *Mission Possible, ETC, Nov 2018;* McKinsey 2018, *Decarbonization of industrial sectors: the next frontier*

Economics: U.S. levelized costs of electricity

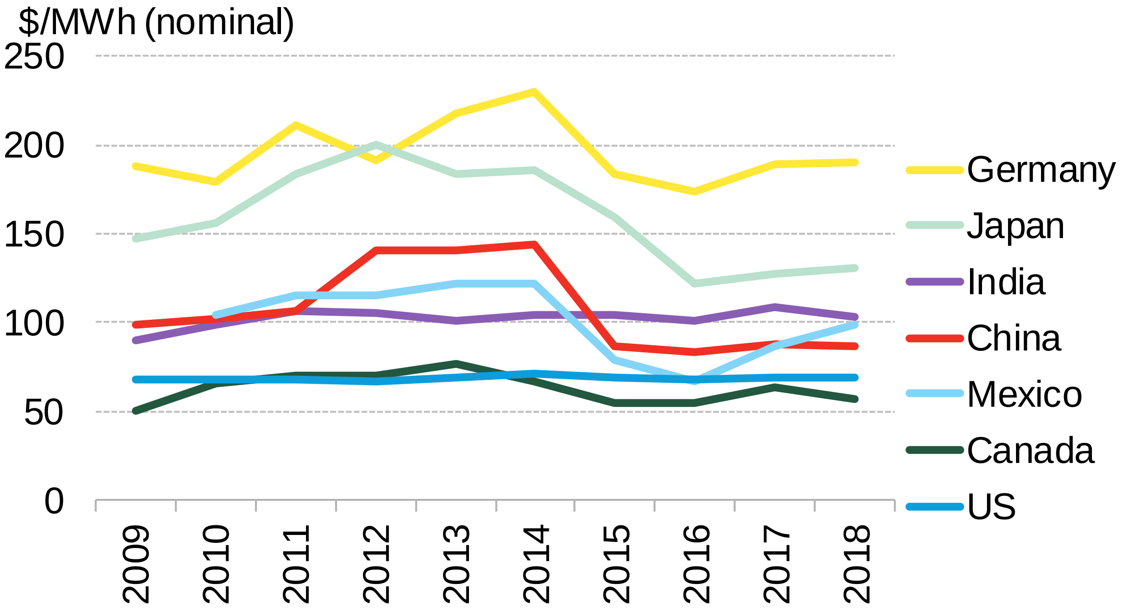
(unsubsidized for new build, 2H 2019)



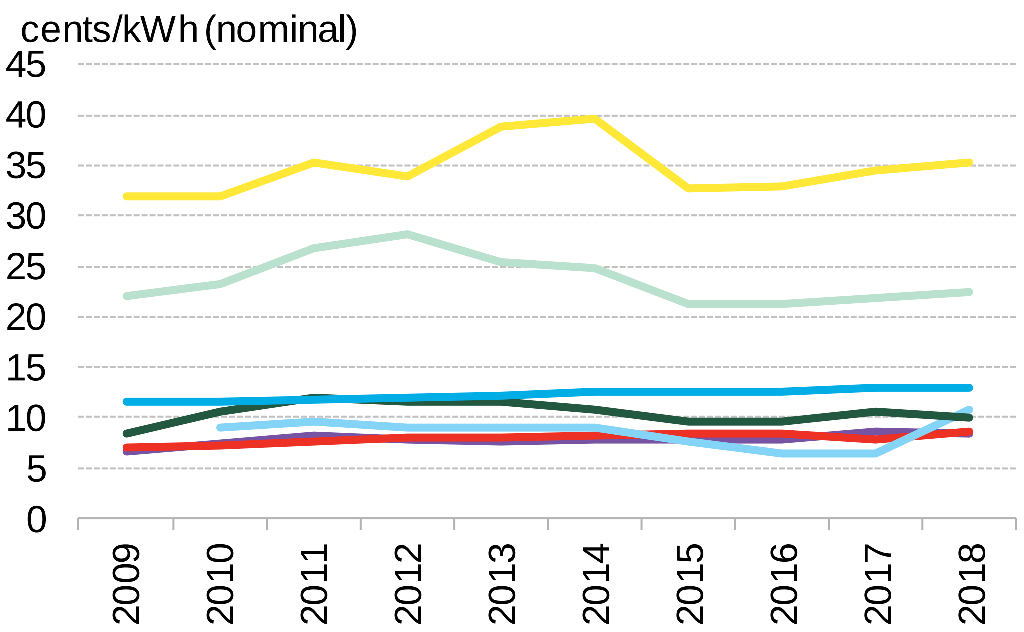
Source: BloombergNEF. Note: The LCOE range represents a range of costs and capacity factors. Battery storage systems (co-located and stand-alone) presented here have four-hour storage. In the case of solar- and wind-plus-battery systems, the range is a combination of capacity factors and size of the battery relative to the power generating asset (25% to 100% of total installed capacity). All LCOE calculations are unsubsidized. Categorization of technologies is based on their primary use case.

Average electricity rates by country

Industrial power prices



Residential power prices



Source: BloombergNEF, government sources (EIA for the U.S.) Notes: Prices are averages (and in most cases, weighted averages) across all regions within the country. Japanese data is for the C&I segment and 2016 figures come from a different source than preceding years.

Solar energy

Electrons could become the lowest cost energy

Electricity is moving from being one of the most expensive energy carriers to that with lowest cost, with solar generation offering highest energy utilization and smallest footprint.

- Highest energy utilization
- Lowest production costs
- Smallest production footprint

Photons

TO END-USER

- Heating
- Lighting

Electrons

TO END-USER

- Power
- Cooking
- Heating/Cooling
- Personal mobility
- Rail

Hydrogen

TO END-USER

- Personal mobility
- Heavy transport
- Industrial heat
- Power
- Rail
- Cooking
- Heating/Cooling

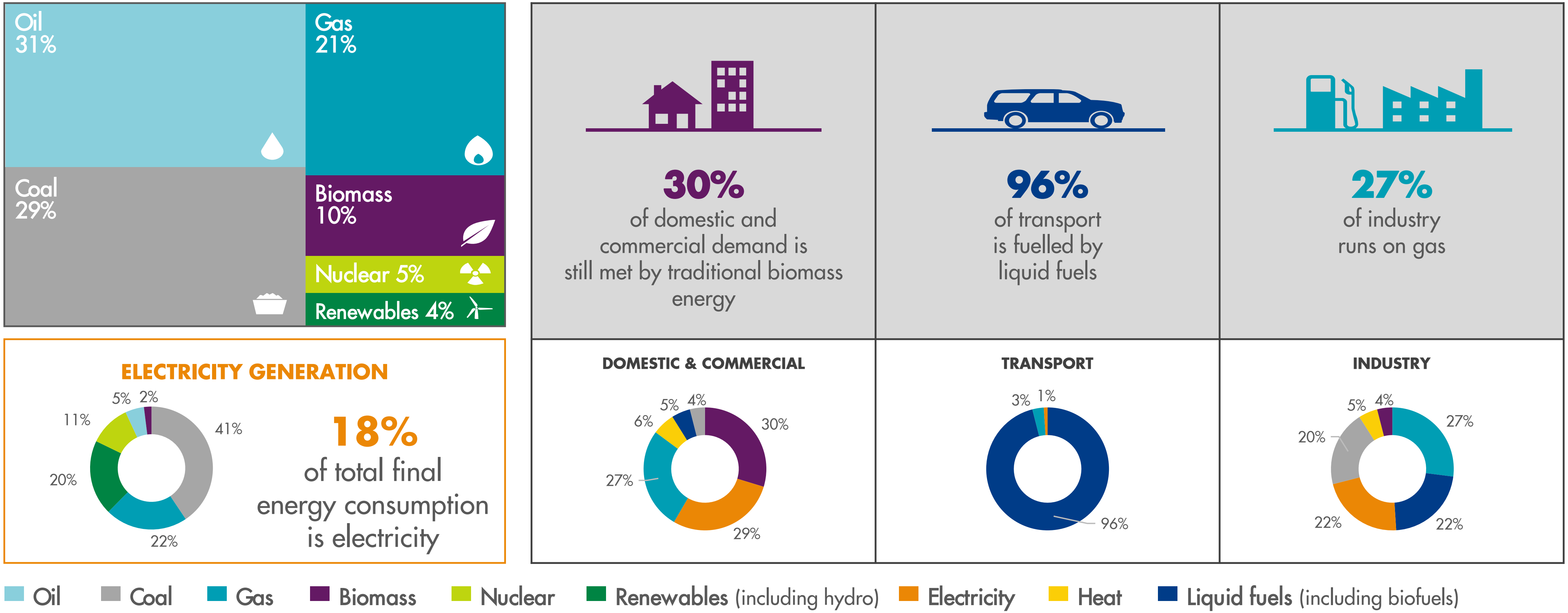
Hydrocarbons

- Highest product utility
- Lowest handling costs
- Most compact use

Today's Energy Mix

Current Global Energy Demand

Energy Consumption by Sector and Consumer Trends

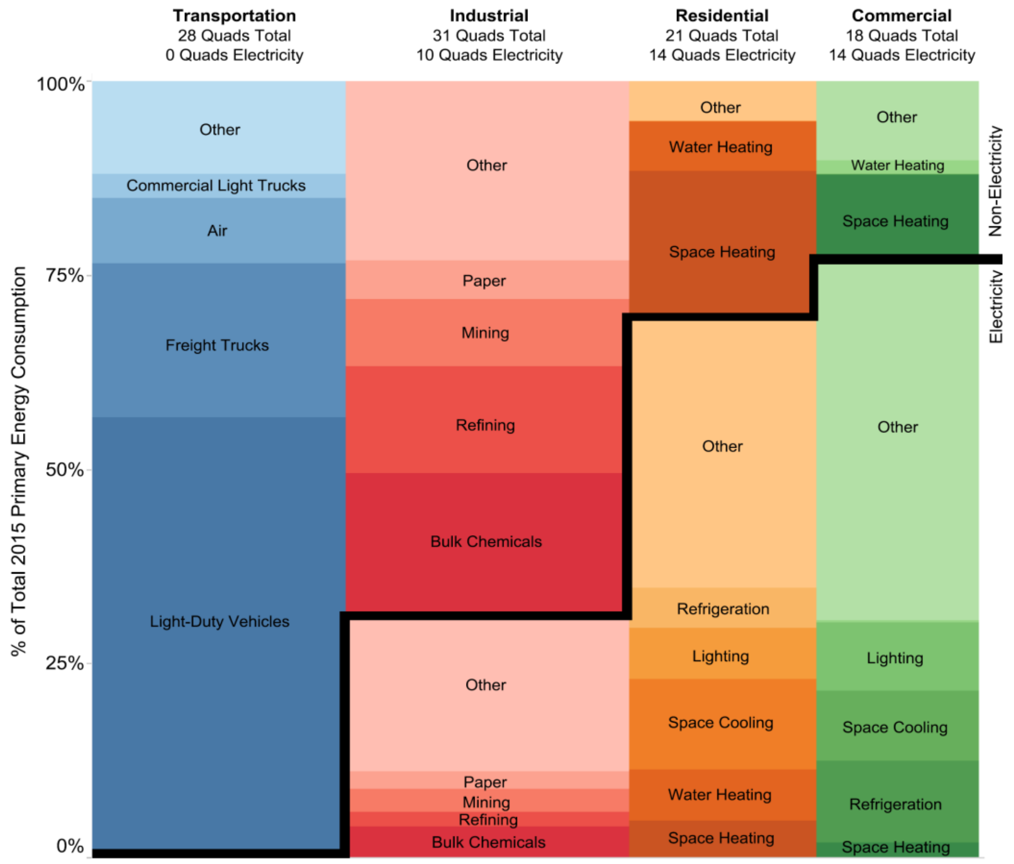


Source: International Energy Agency, World Energy Outlook

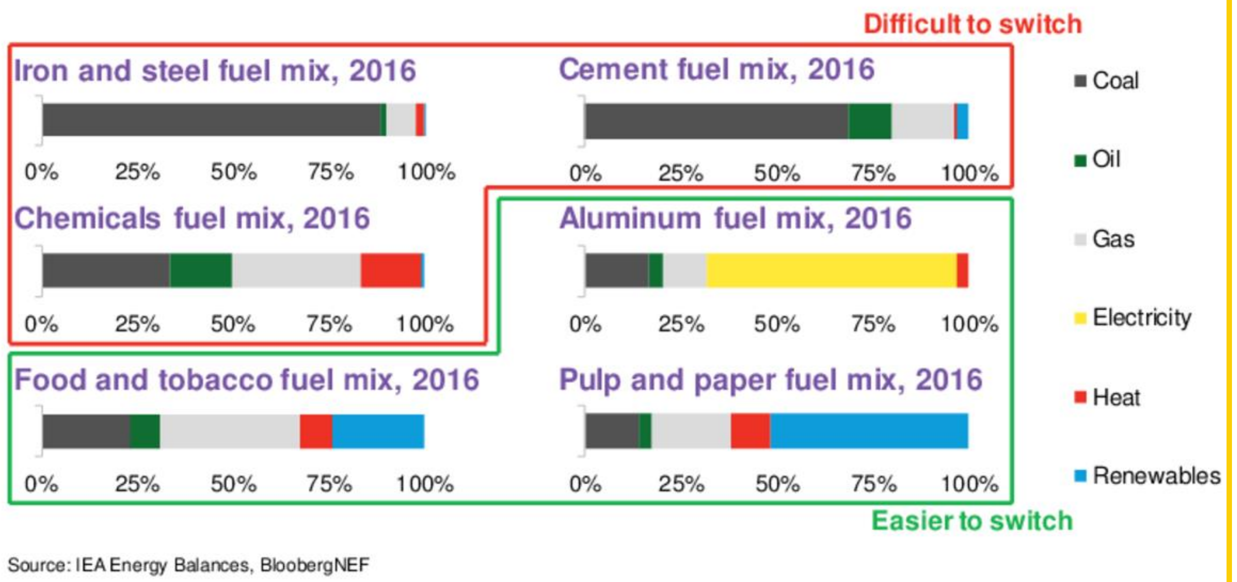
Electrification lags in transportation & industry

Sector diversity requires multiple technology options to increase electrification

US energy use by sector



Global fuel mix – industrial sector



Sources: *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050*. NREL/TP-6A20-70485; BNEF, .

Electricity in the industrial sector

- 1892 — Chlor Alkali
- 1888 — Aluminum
- 1902 — Air separation

\+

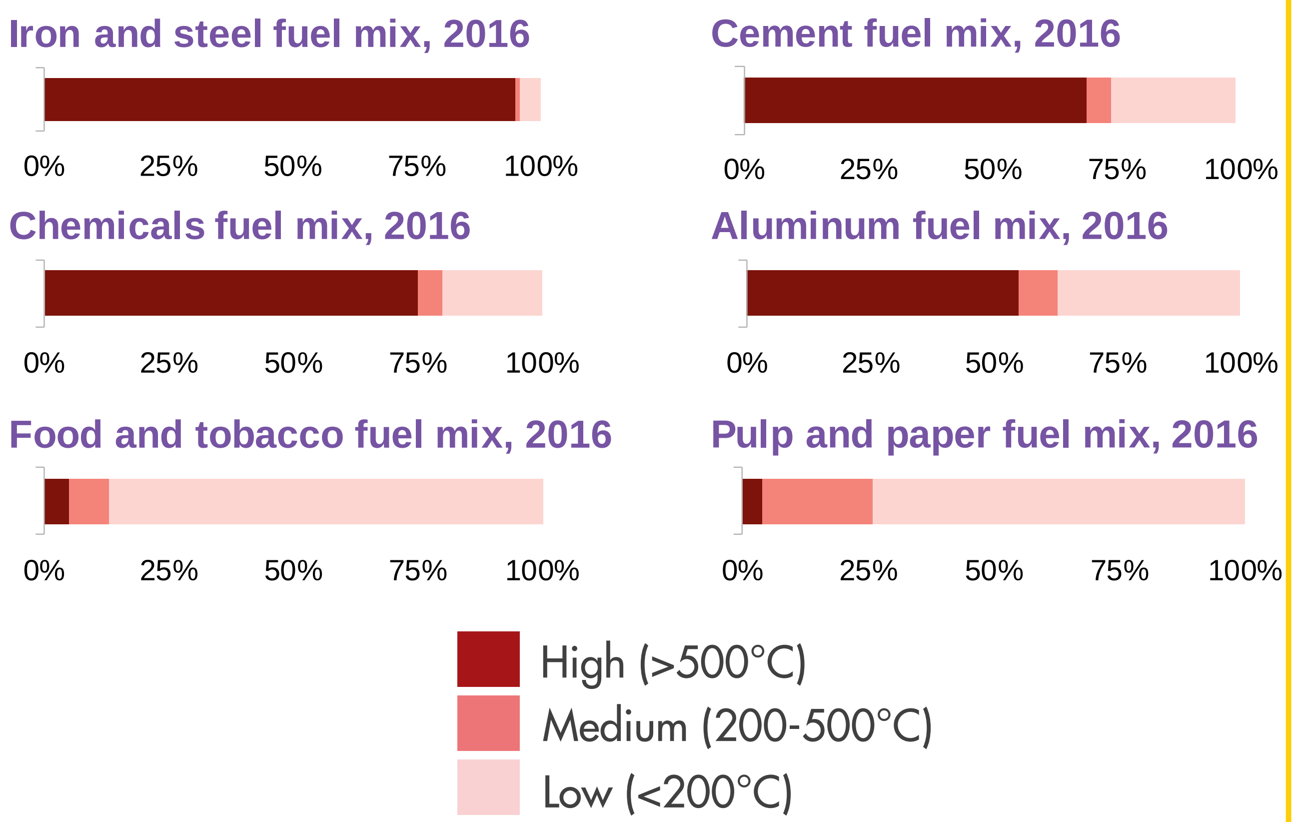
- Hydrogen
- Base Chemicals
- Specialty Chemicals

What will this require?

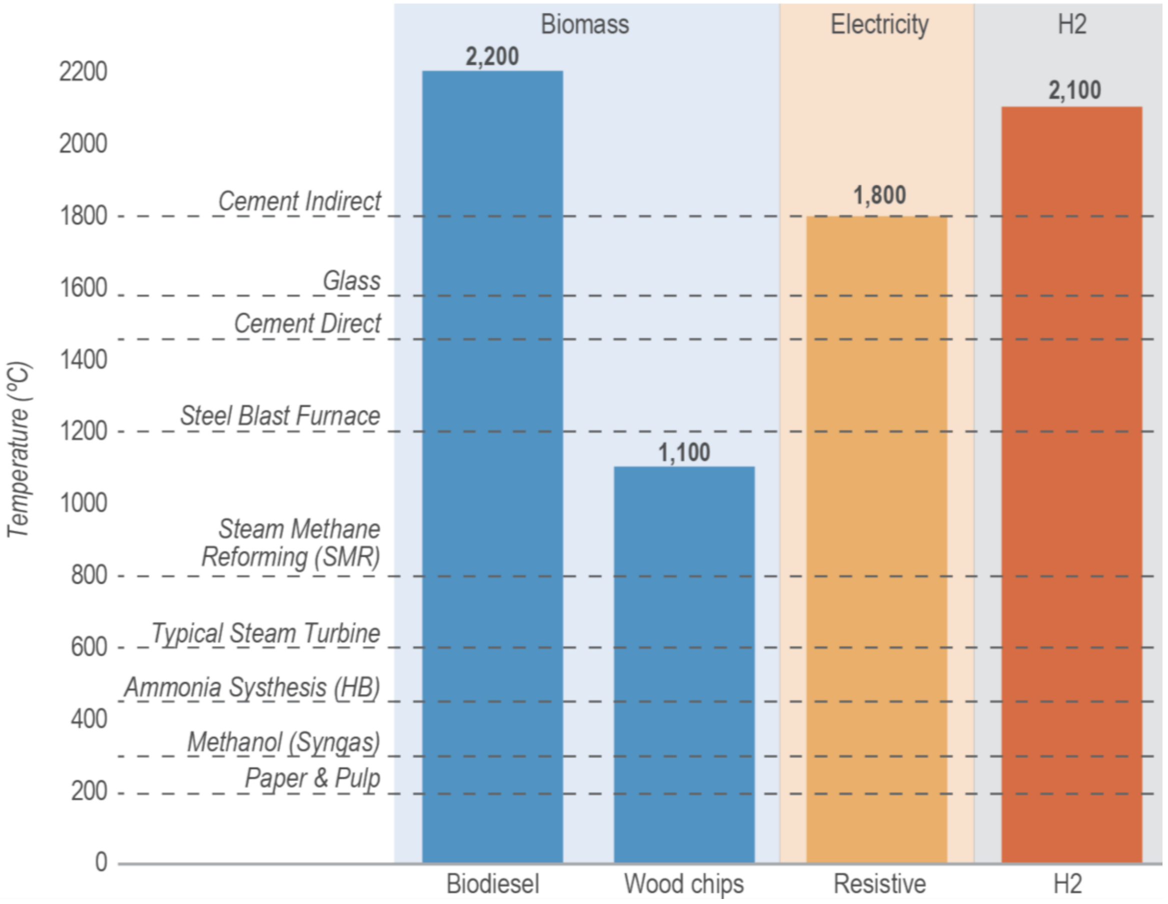
Process heating needs for industrial applications

Electrifying heat could be a significant lever

Heat requirements by sub-sector



Temperature requirements by process



Sources: European Commission, IEA Energy Balances, BloombergNEF; McKinsey 2018, *Decarbonization of industrial sectors: the next frontier; Mission Possible,* ETC, Nov 2018

What innovations are needed to make this reality?

Range of temperatures needed provides options for technologies

Step changes highlighted for improvements for industrial applications

ELECTRIFICATION

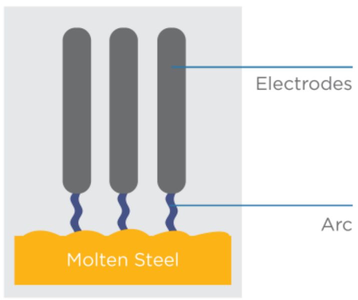
- Cheaper and more efficient batteries
- Electric furnaces for cement and chemicals
- Electrochemical reduction of iron for steel production

BIOCHEMISTRY AND SYNTHETIC CHEMISTRY

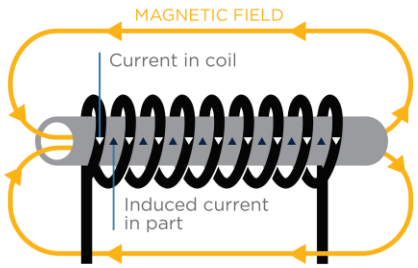
- Increased efficiency in biomass transformation
- Bioenergy and bio-feedstocks from lignocellulosic sources and algae
- Synthetic chemistry, including direct air capture of CO_2

Potential technologies being evaluated

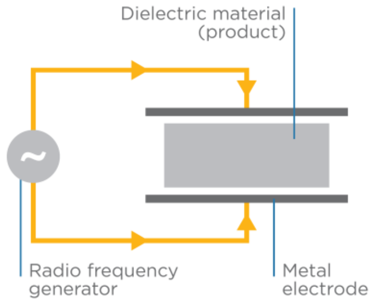
ELECTRIC ARC HEATING



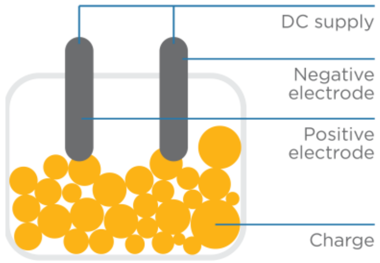
INDUCTION HEATING



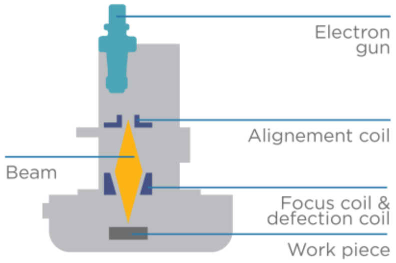
DIELECTRIC HEATING



DIRECT RESISTANCE HEATING



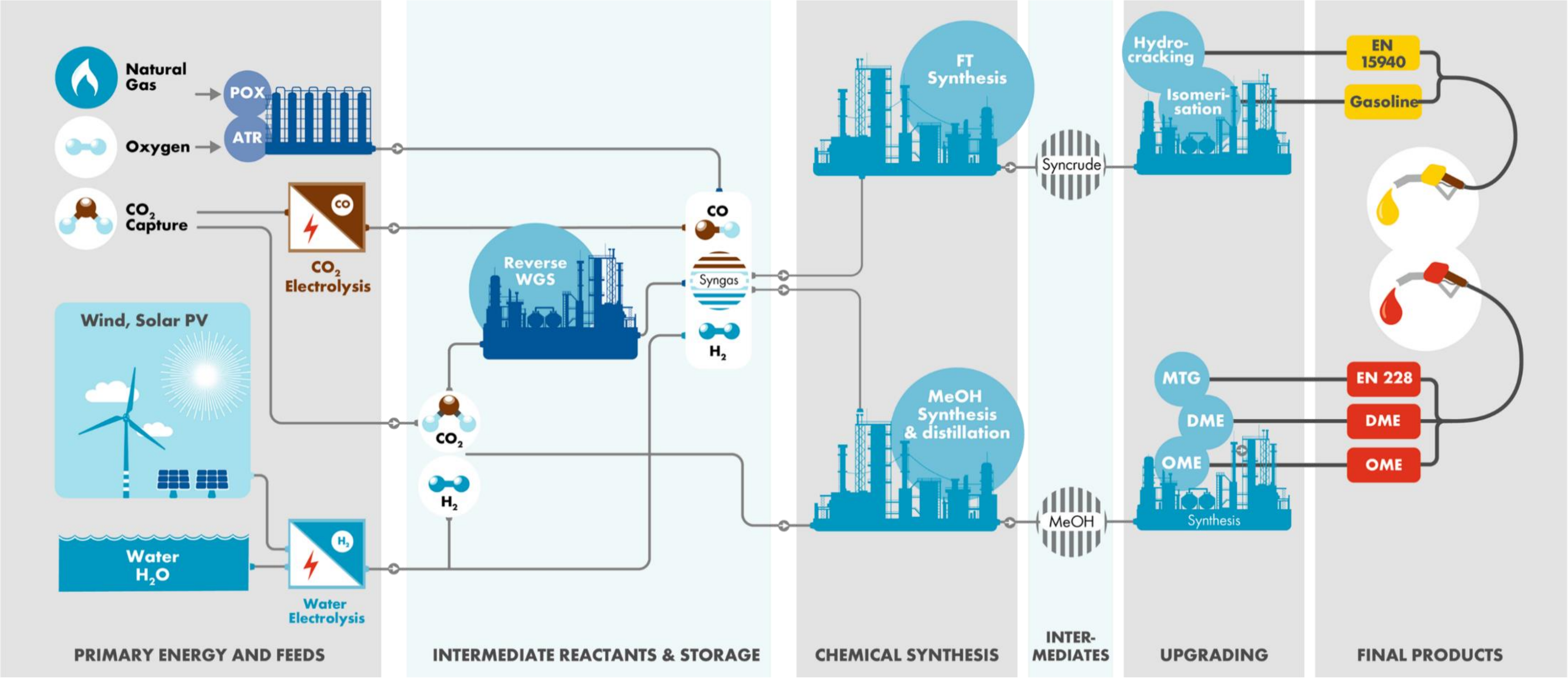
ELECTRON BEAM HEATING



Sources: ICEF Industrial Heat Decarbonization Roadmap, Oct 2019; Friedmann et al., Low Carbon Heat Solutions for Heavy Industry, Oct 2019

Moving toward synthetic dense energy carriers

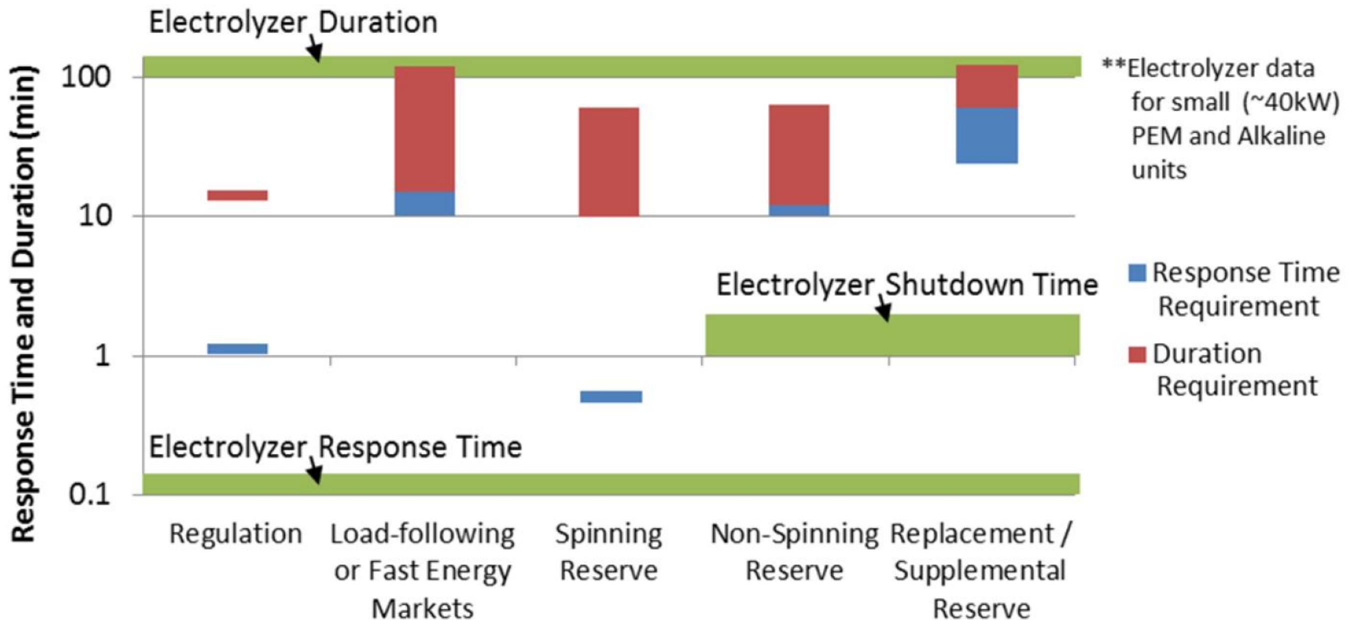
Significant role for electrified process technologies



Hydrogen as an example of flexible demand

Continued improvement in technologies & service provision needed to realize opportunities

	ALKALINE	PEM
Load range	15–100 % nominal load	0–160 % nominal load
Start-up (warm – cold)	1–10 minutes	1 second–5 minutes
Ramp-up / ramp-down	0.2–20 %/second	100 %/second
Shutdown	1–10 minutes	Seconds



Observations from NREL study

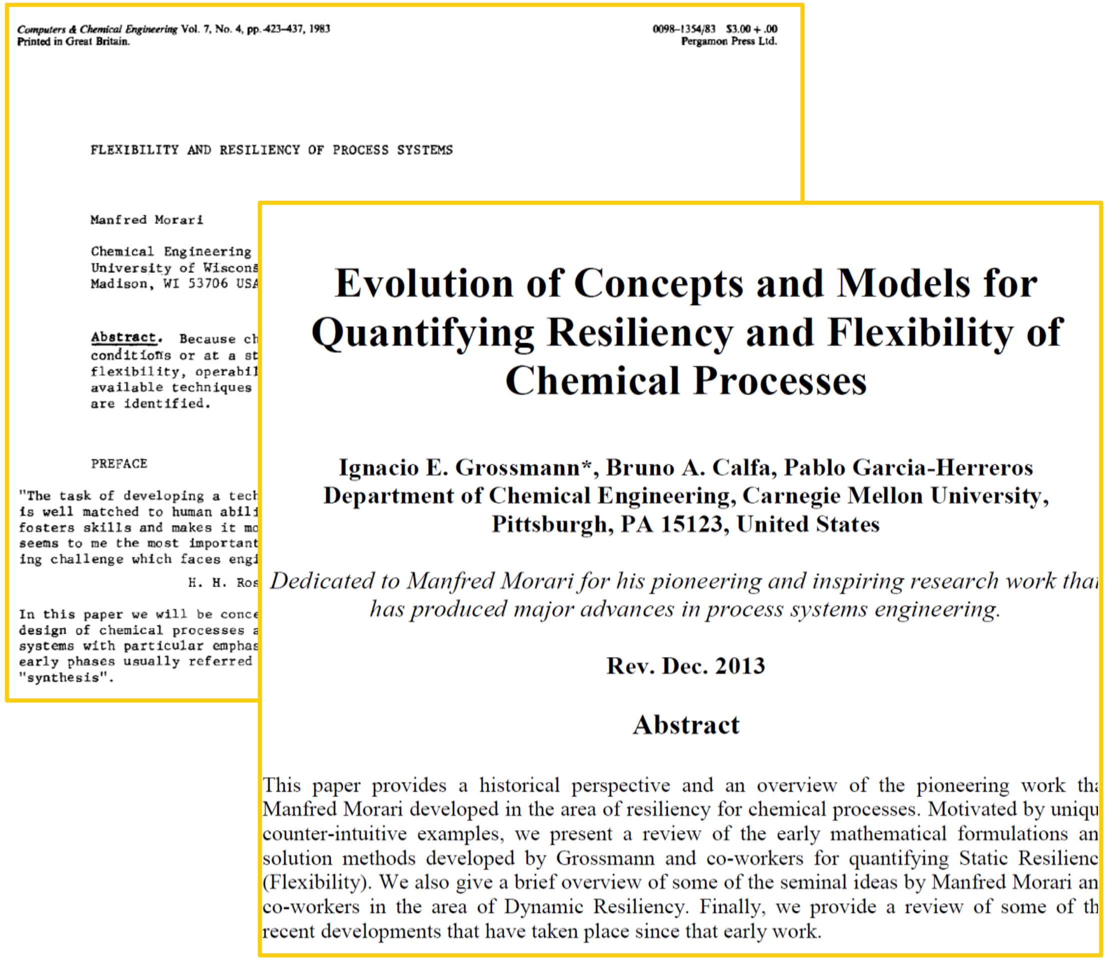
- PEM response is faster than alkaline
- Ramp up is faster than ramp down
- Both are sufficiently fast to comply with market requirements at the time of the study

Data on the impacts of cycling the equipment remains quite limited

Sources: IRENA (2018), Hydrogen from renewable power: Technology outlook for the energy transition; NREL/TP-5400-61758, Sept 2014.

Resilience in integrated systems: flexible, operable, and controllable

Concepts are similar in chemical processes & electrical systems



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Pergamon Press Ltd.

FLEXIBILITY AND RESILIENCY OF PROCESS SYSTEMS

Manfred Morari

Chemical Engineering
University of Wiscons
Madison, WI 53706 USA

Abstract. Because ch
conditions or at a st
flexibility, operabil
available techniques
are identified.

PREFACE

"The task of developing a tech
is well matched to human abili
fosters skills and makes it mo
seems to me the most important
ing challenge which faces engi
H. H. Ros

In this paper we will be conce
design of chemical processes a
systems with particular emphas
early phases usually referred
"synthesis".

Evolution of Concepts and Models for Quantifying Resiliency and Flexibility of Chemical Processes

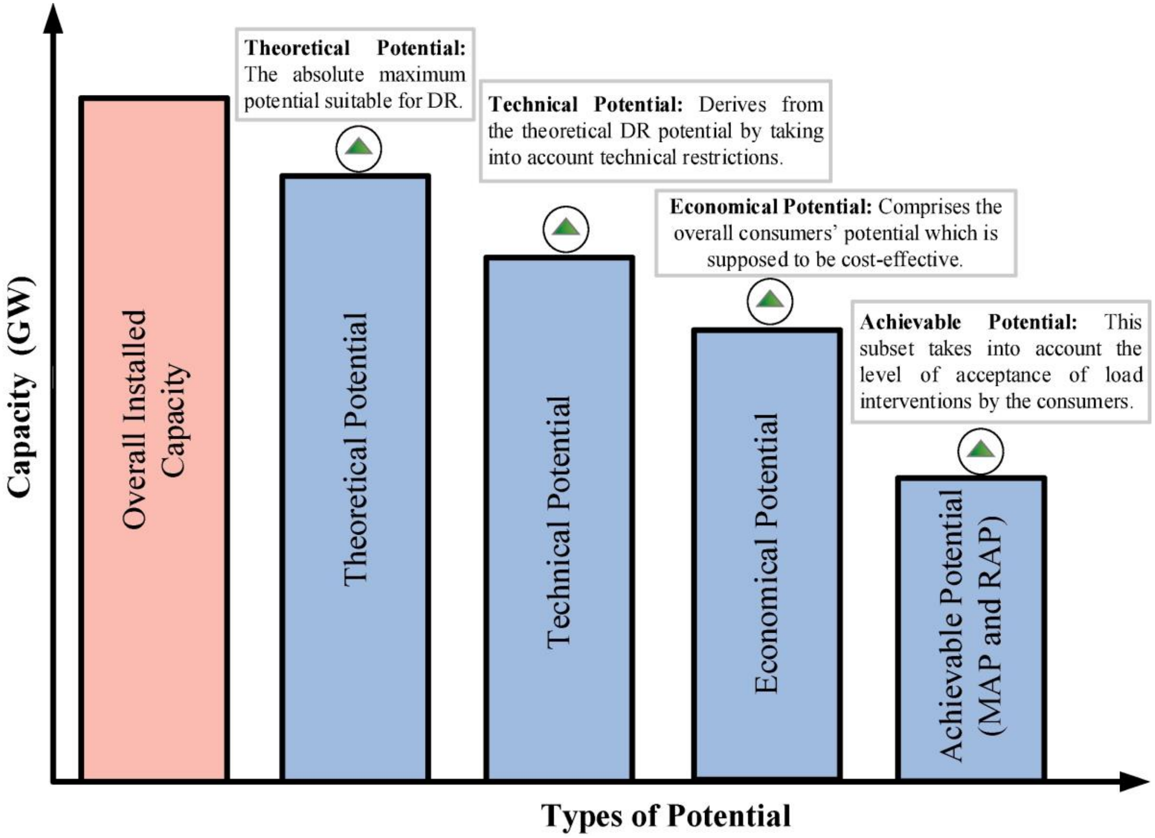
Ignacio E. Grossmann*, Bruno A. Calfa, Pablo Garcia-Herreros
Department of Chemical Engineering, Carnegie Mellon University, Pittsburgh, PA 15123, United States

Dedicated to Manfred Morari for his pioneering and inspiring research work that has produced major advances in process systems engineering.

Rev. Dec. 2013

Abstract

This paper provides a historical perspective and an overview of the pioneering work tha
Manfred Morari developed in the area of resiliency for chemical processes. Motivated by uniqu
counter-intuitive examples, we present a review of the early mathematical formulations an
solution methods developed by Grossmann and co-workers for quantifying Static Resilienc
(Flexibility). We also give a brief overview of some of the seminal ideas by Manfred Morari an
co-workers in the area of Dynamic Resiliency. Finally, we provide a review of some of th
recent developments that have taken place since that early work.



For successful DSM in the chemical industry, product storage is nearly always required to maintain these critical characteristics

Sources: DOI 10.1002/aic.15221; https://doi.org/10.1016/j.energy.2019.05.009; https://doi.org/10.1016/0098-1354(83)80021-0

A more detailed view at sector coupling

Incorporating flexibility & resilience throughout will be key to overall operability

		Role of direct electrification	Role of electricity-based fuels: Hydrogen	Role of electricity-based fuels: Ammonia	Role of electricity-based fuels: Synfuels
Industry	Cement	Electrification of kiln heat (process emissions remain)	As heat source		
Industry	Steel	Electrification of furnace heat Direct iron electrolysis	As reduction agent and heat source		
Industry	Plastics	Electrification of furnace heat	As heat source		Potential role as plastics feedstock
Transport	Heavy-road transport	Battery electric vehicle (BEV) Catenary overhead wiring	Fuel cell electric vehicle (FCEV)		
Transport	Shipping	Battery electric for short distance Cruise and RoPax ships	Burnt in ICE or used in fuel cells	Burnt in ICE or used in fuel cells	
Transport	Aviation	Battery electric for short distance	Fuel cell electric for medium distance		In conventional jet engine
Building heating		Through heat pumps or induction	As substitute for natural gas		
Electricity system			Energy storage	Energy storage Transportation of H_2	

Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Sources: *Mission Possible*, ETC, Nov 2018

Closing thoughts

- Growth in renewable electricity presents many opportunities alongside new research needs.
- The chemical process industry has a unique opportunity to incorporate deep knowledge of systems design, optimization, and control into the broader energy system.
- Electrification, electrochemical energy conversion, & multiple forms of storage have the potential to play key roles in future products, processes, and services.
- Thank you for your attention!

Acknowledgements

Many thanks to the following for supporting the work described today

Our global external research partners & their teams

Shell internal teams, including the Electrification Platform

Numerous former colleagues who laid the foundations for this work to exist and on which we continue to build.