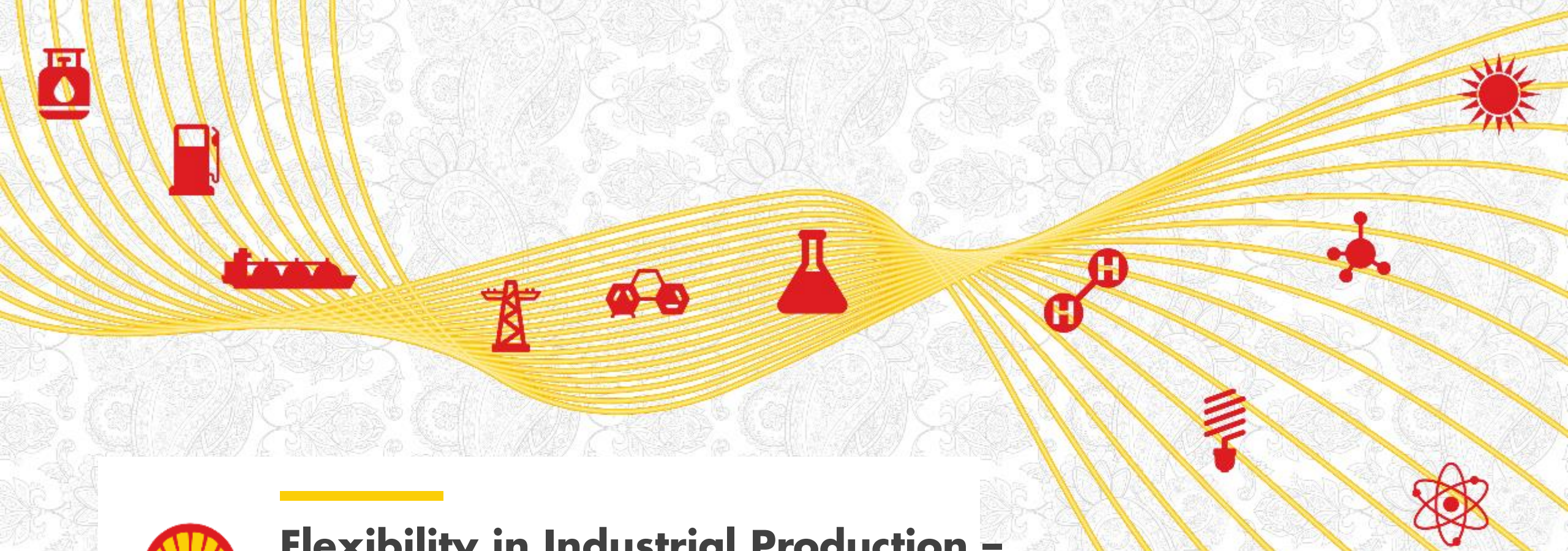




Flexibility in Industrial Production – A view on status and prospects

Elizabeth Endler

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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.

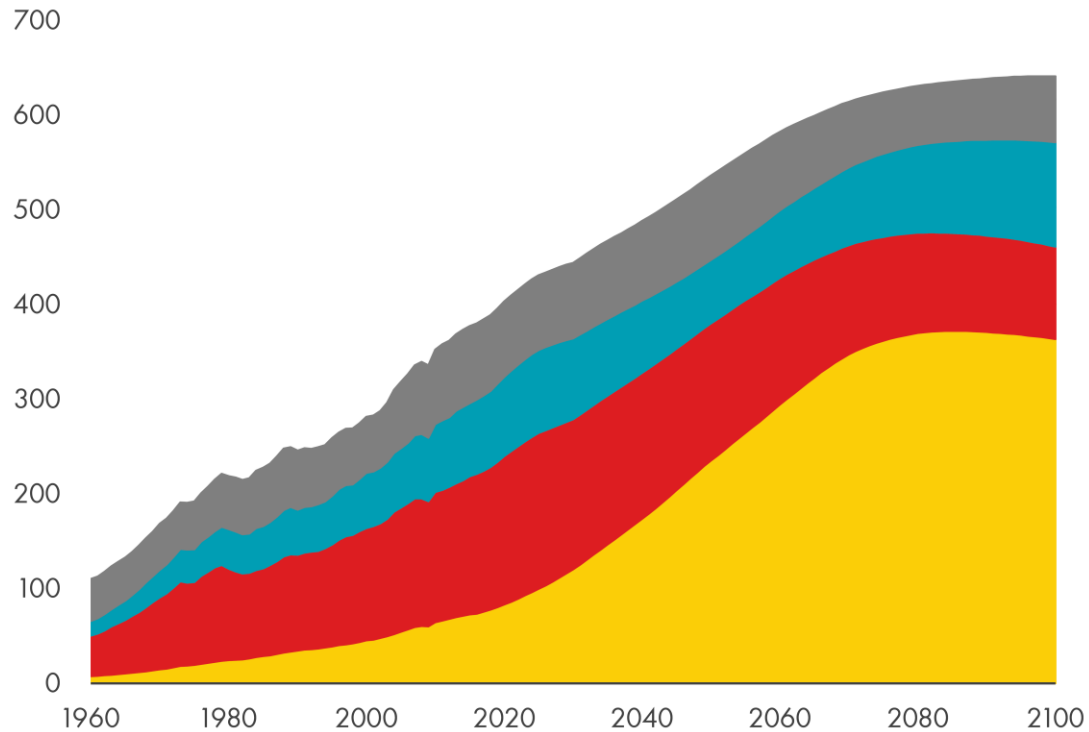
This presentation contains forward-looking statements concerning the financial condition, results of operations and businesses of Royal Dutch Shell. All statements other than statements of historical fact are, or may be deemed to be, forward-looking statements. Forward-looking statements are statements of future expectations that are based on management’s current expectations and assumptions and involve known and unknown risks and uncertainties that could cause actual results, performance or events to differ materially from those expressed or implied in these statements. Forward-looking statements include, among other things, statements concerning the potential exposure of Royal Dutch Shell to market risks and statements expressing management’s expectations, beliefs, estimates, forecasts, projections and assumptions. These forward-looking statements are identified by their use of terms and phrases such as “anticipate”, “believe”, “could”, “estimate”, “expect”, “goals”, “intend”, “may”, “objectives”, “outlook”, “plan”, “probably”, “project”, “risks”, “schedule”, “seek”, “should”, “target”, “will” and similar terms and phrases. There are a number of factors that could affect the future operations of Royal Dutch Shell and could cause those results to differ materially from those expressed in the forward-looking statements included in this [report], including (without limitation): (a) price fluctuations in crude oil and natural gas; (b) changes in demand for Shell’s products; (c) currency fluctuations; (d) drilling and production results; (e) reserves estimates; (f) loss of market share and industry competition; (g) environmental and physical risks; (h) risks associated with the identification of suitable potential acquisition properties and targets, and successful negotiation and completion of such transactions; (i) the risk of doing business in developing countries and countries subject to international sanctions; (j) legislative, fiscal and regulatory developments including regulatory measures addressing climate change; (k) economic and financial market conditions in various countries and regions; (l) political risks, including the risks of expropriation and renegotiation of the terms of contracts with governmental entities, delays or advancements in the approval of projects and delays in the reimbursement for shared costs; and (m) changes in trading conditions. No assurance is provided that future dividend payments will match or exceed previous dividend payments. All forward-looking statements contained in this presentation are expressly qualified in their entirety by the cautionary statements contained or referred to in this section. Readers should not place undue reliance on forward-looking statements. Additional risk factors that may affect future results are contained in Royal Dutch Shell’s 20-F for the year ended December 31, 2019 (available at www.shell.com/investor and www.sec.gov). These risk factors also expressly qualify all forward looking statements contained in this presentation and should be considered by the reader. Each forward-looking statement speaks only as of the date of this presentation, **16 April 2020**. Neither Royal Dutch Shell plc nor any of its subsidiaries undertake any obligation to publicly update or revise any forward-looking statement as a result of new information, future events or other information. In light of these risks, results could differ materially from those stated, implied or inferred from the forward-looking statements contained in this presentation. This presentation may contain references to Shell’s website. These references are for the readers’ convenience only. Shell is not incorporating by reference any information posted on www.shell.com. We may have used certain terms, such as resources, in this presentation that United States Securities and Exchange Commission (SEC) strictly prohibits us from including in our filings with the SEC. U.S. Investors are urged to consider closely the disclosure in our Form 20-F, File No 1-32575, available on the SEC website www.sec.gov.

Energy outlook

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

Global end-use energy consumption

Exajoules



Solid



Gaseous



Liquid



Electricity



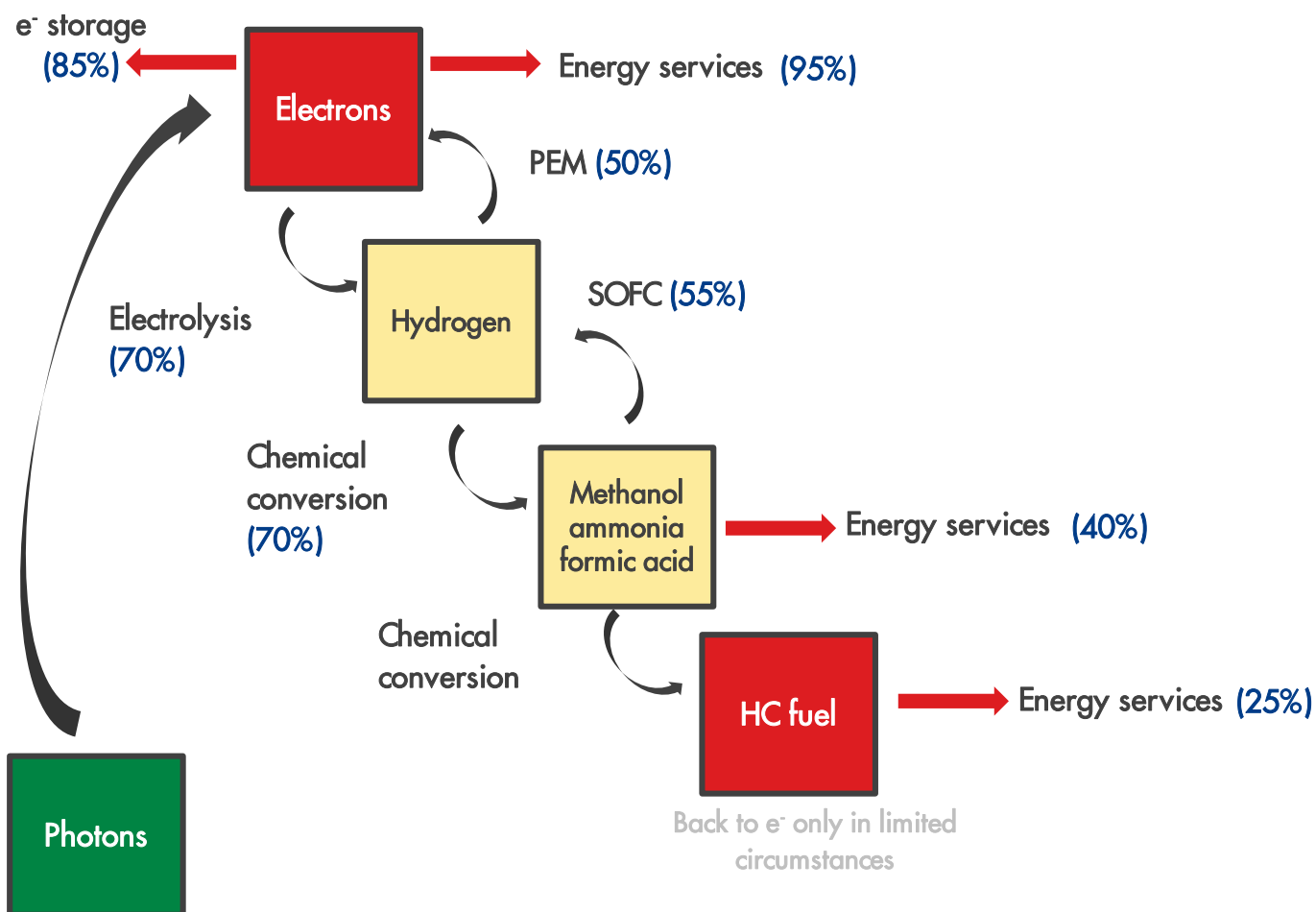
More people

More prosperity

Lower carbon

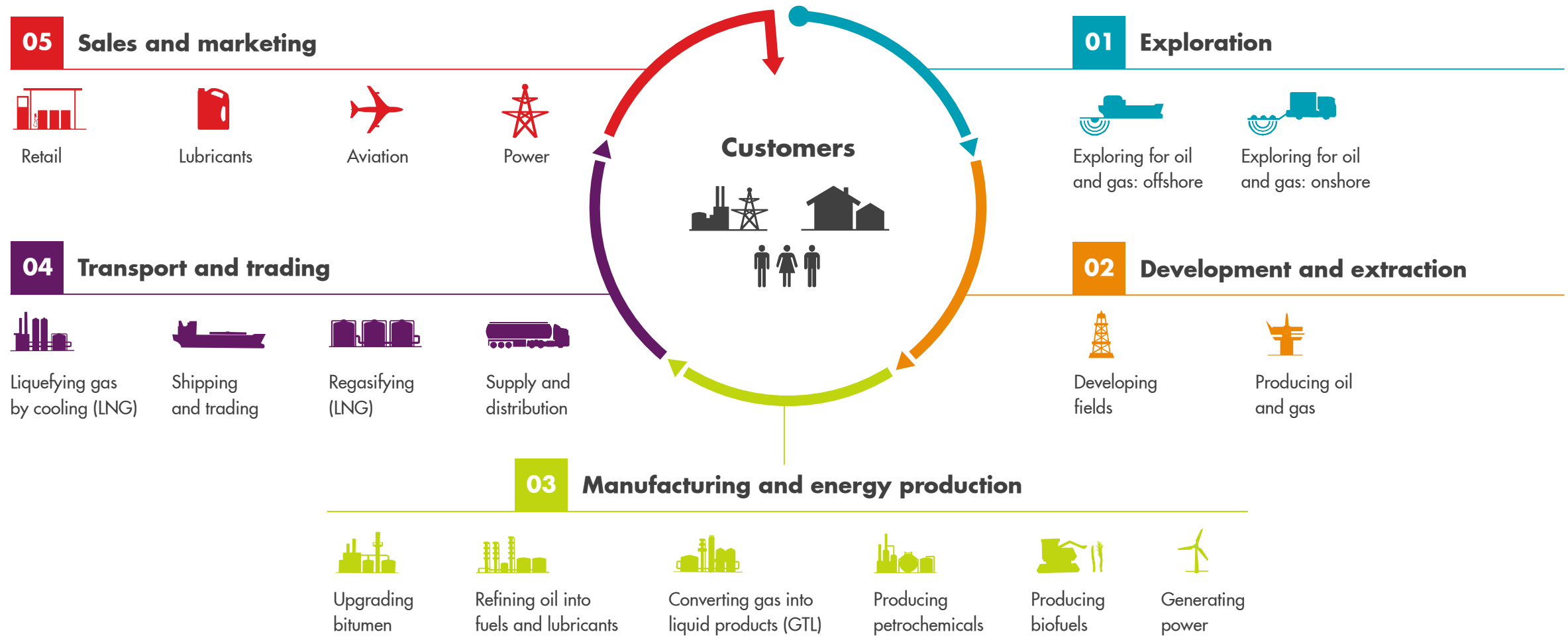
Electricity: high quality energy

Significant reduction in primary energy demand to deliver equivalent services

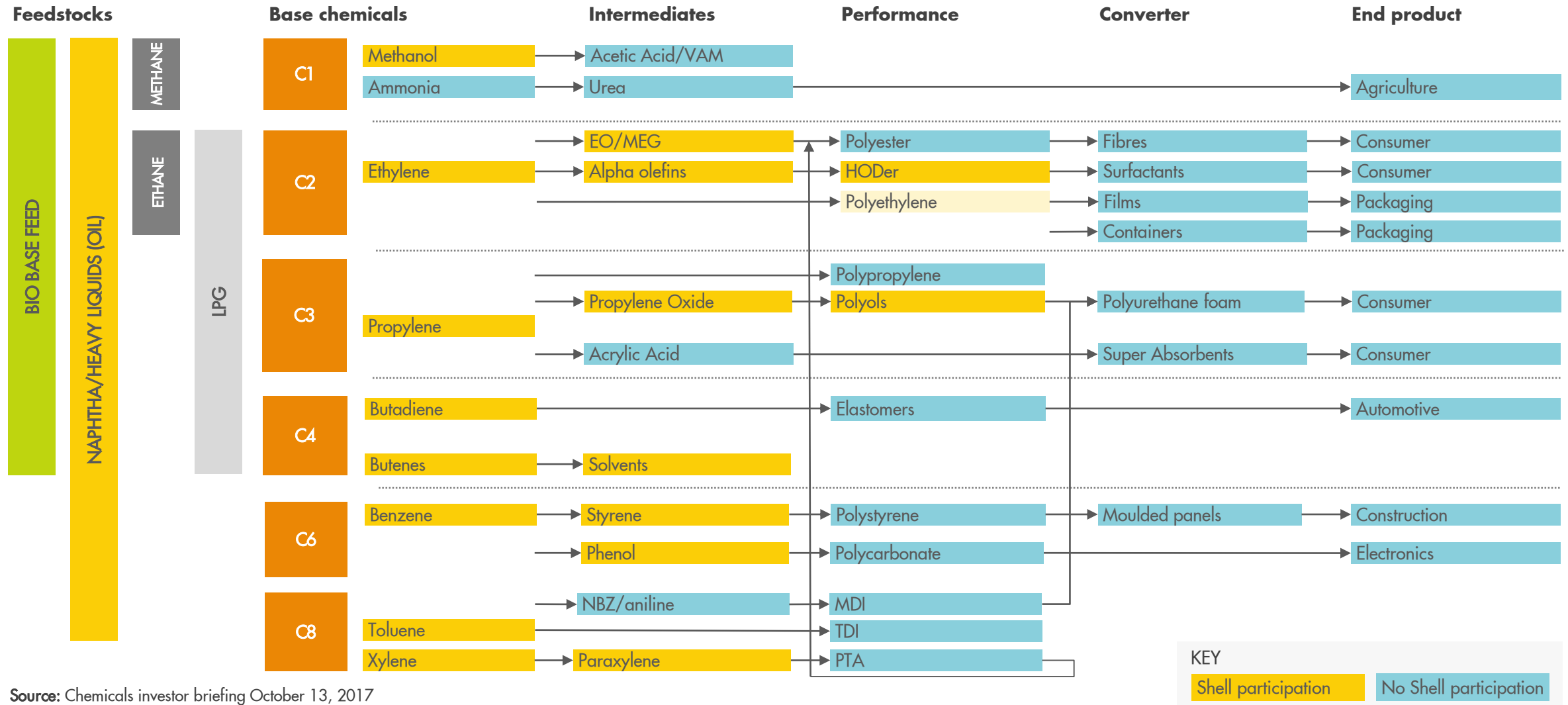


The lower the conversion process efficiencies for each step, the more advantaged “electric-only” pathways are on a primary energy basis

Shell business overview



Chemicals value chains

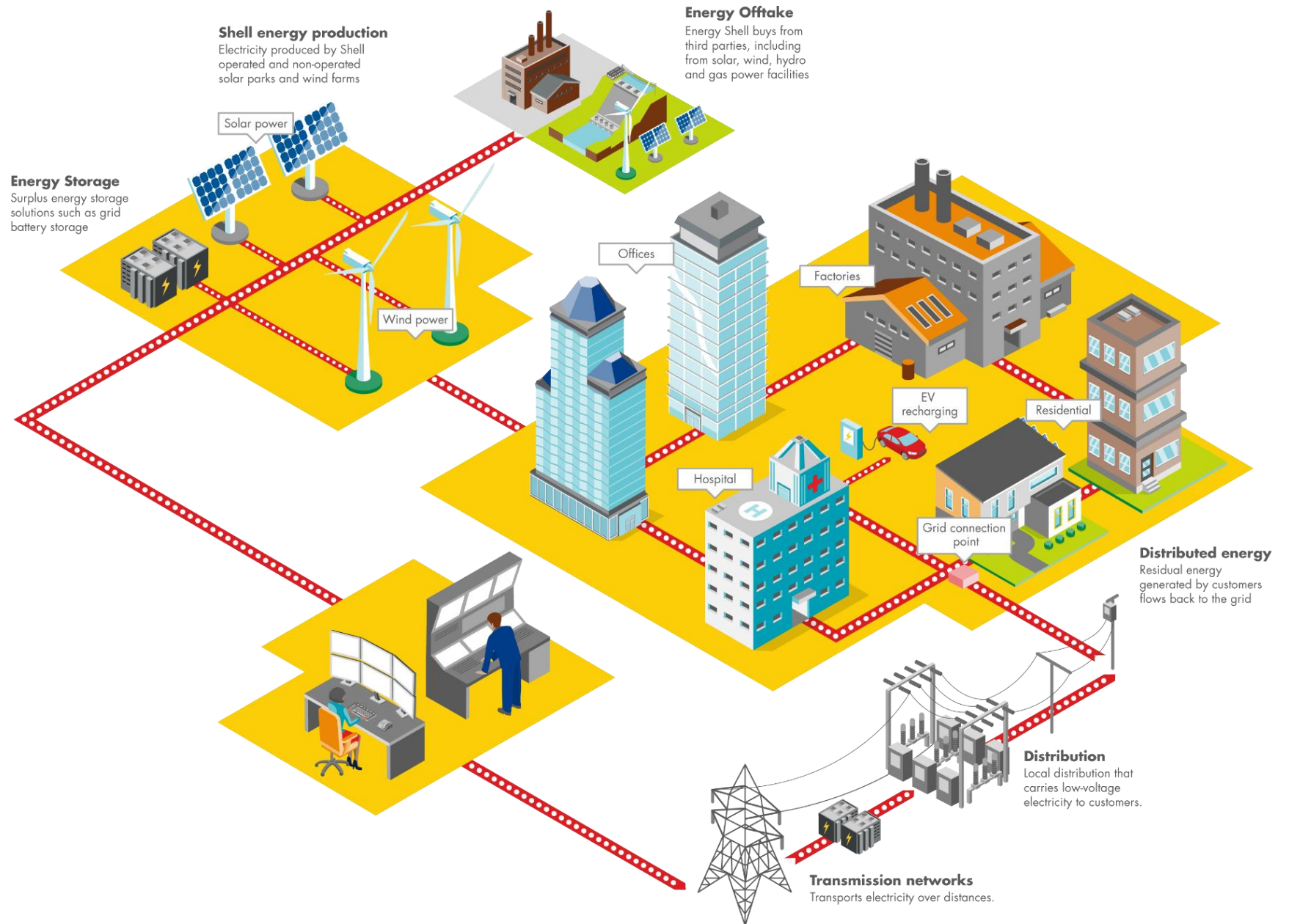


Source: Chemicals investor briefing October 13, 2017

Shell and the integrated power system

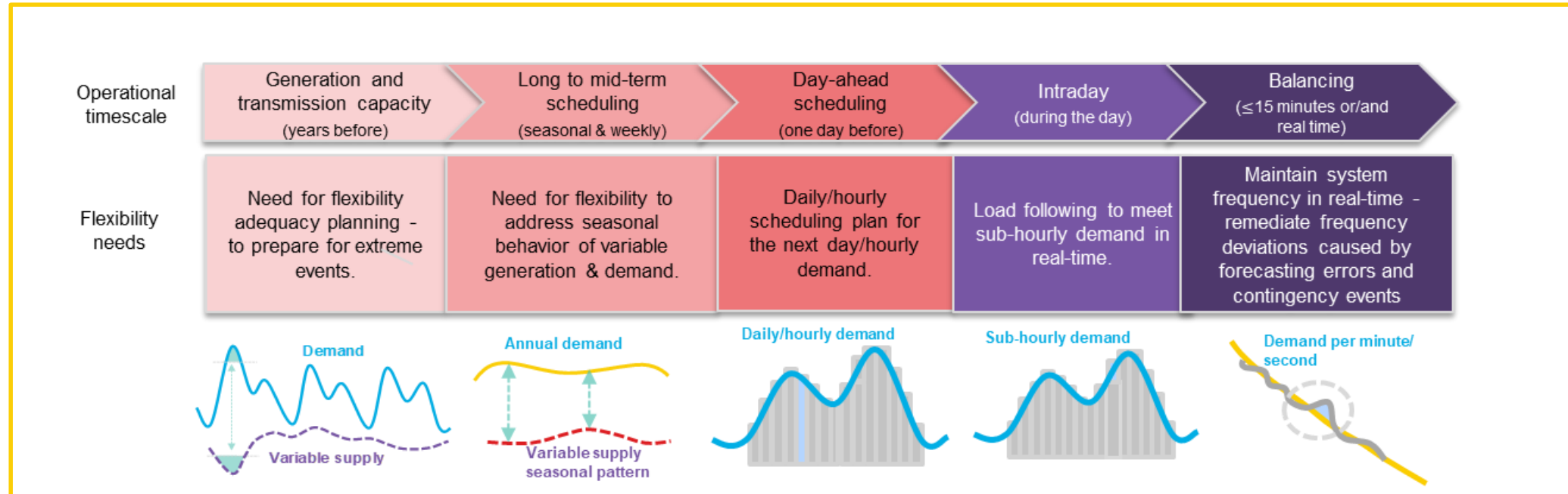
Investments and acquisitions

- 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

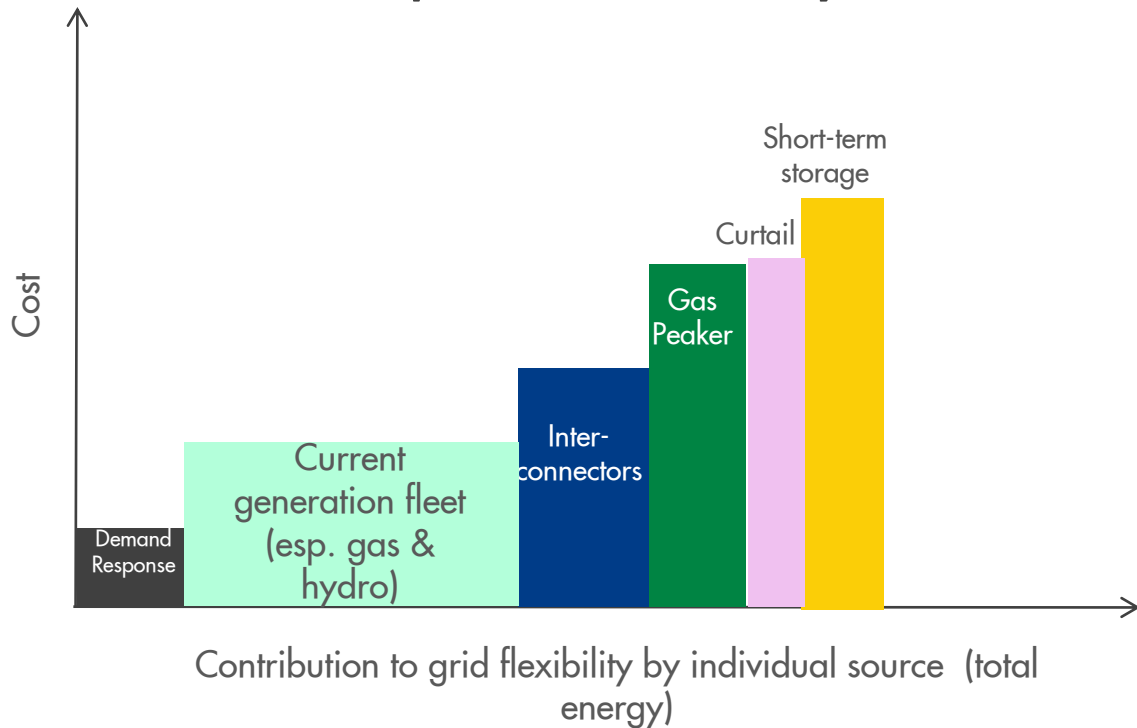
Manufacturing processes have analogous planning, scheduling, optimization, & control timescales



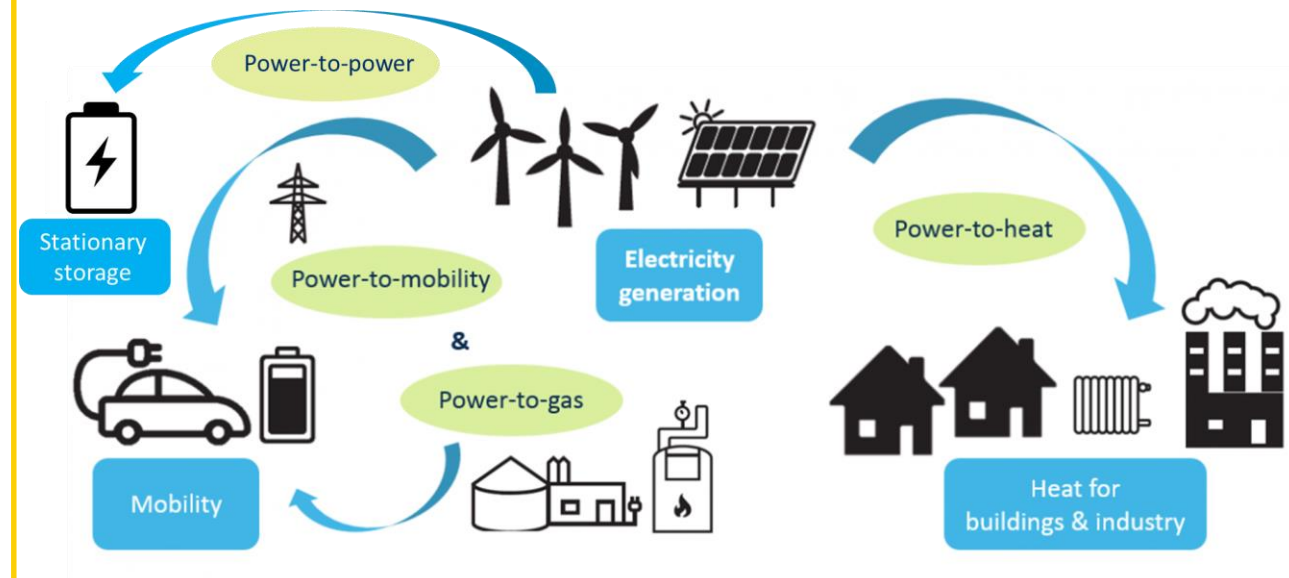
IRENA defines flexibility as “the capability of a power system to cope with the variability and uncertainty that solar and wind energy introduce at different time scales, from the very short to the long term, minimising curtailment of power from these variable renewable energy (VRE) sources and reliably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

Flexibility can be provided in multiple ways by multiple sources

Conceptual representation of today: power sector only

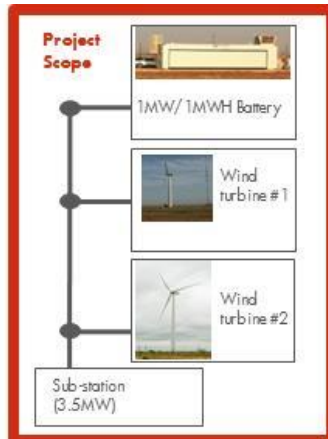


Potential future: Sector Coupling



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



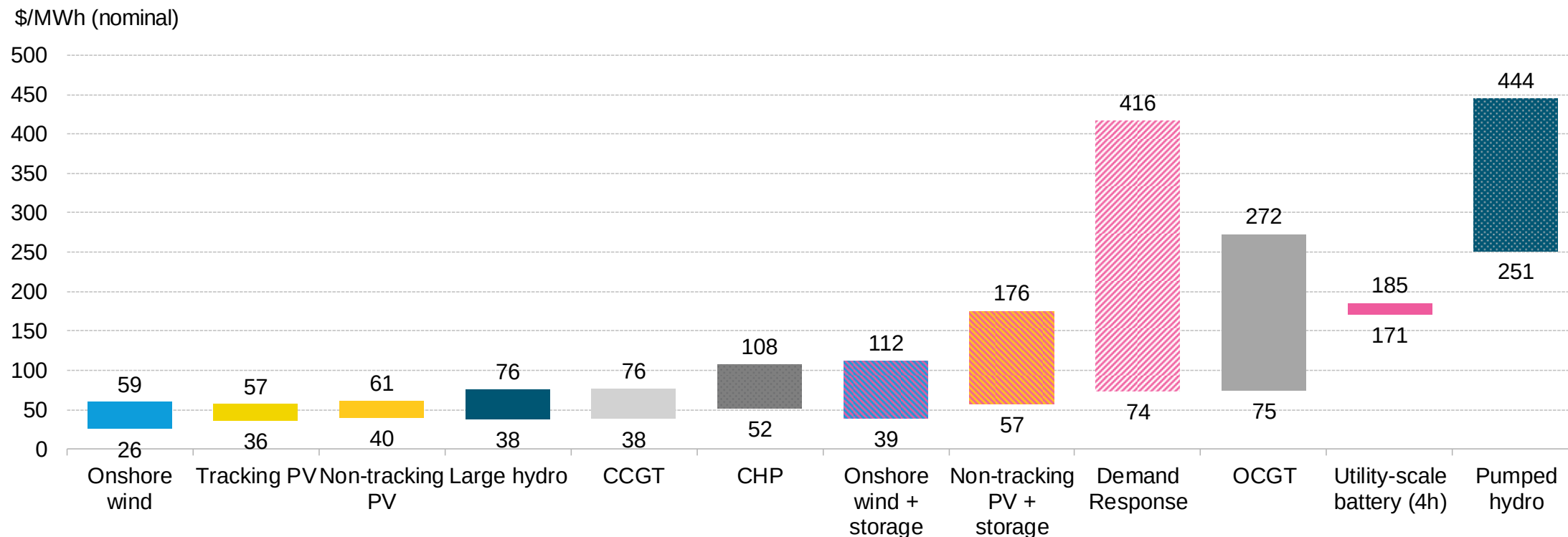
Cost curves are based on global weighted averages. Fossil fuel-fired power generation costs are shown for G20 countries in 2017 and vary between USD 0.05 and USD 0.17/kWh.

Notional power cost thresholds for large-scale electrification

Cement: \$25-50/MWh
Steel (via H₂): \$25-40/MWh
Ethylene: \$15-\$25/MWh

Economics: U.S. levelized costs of electricity

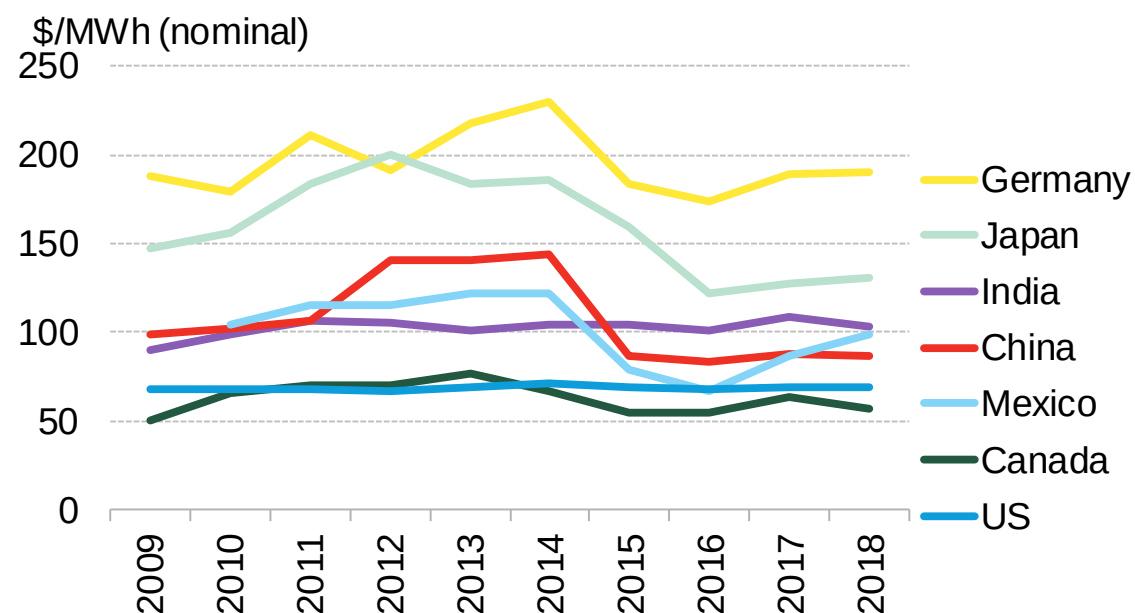
(unsubsidized for new build, 2H 2019)



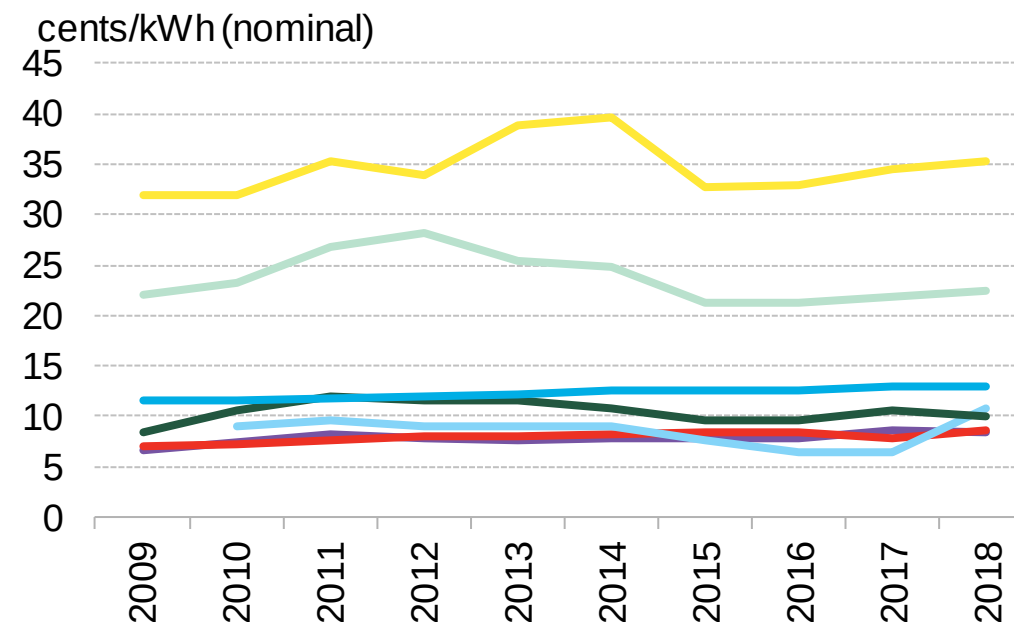
Source: BloombergNEF. Note: The LCOE range represents a range of costs and capacity factors. Battery storage systems (co-located and stand-alone) presented here have four-hour storage. In the case of solar- and wind-plus-battery systems, the range is a combination of capacity factors and size of the 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

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

Hydrocarbons

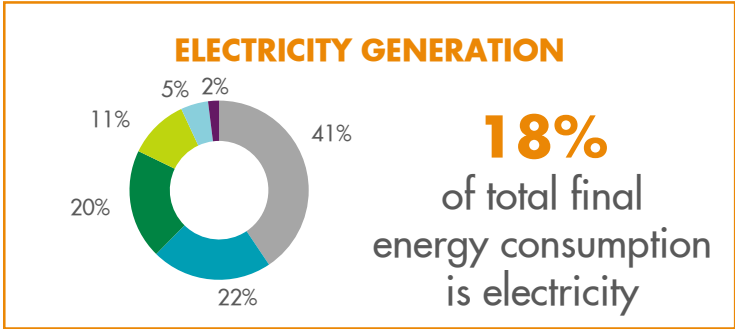
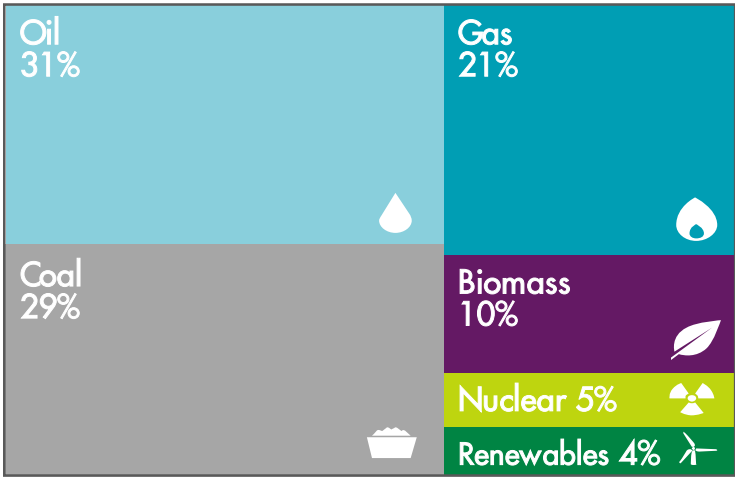
TO END-USER

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

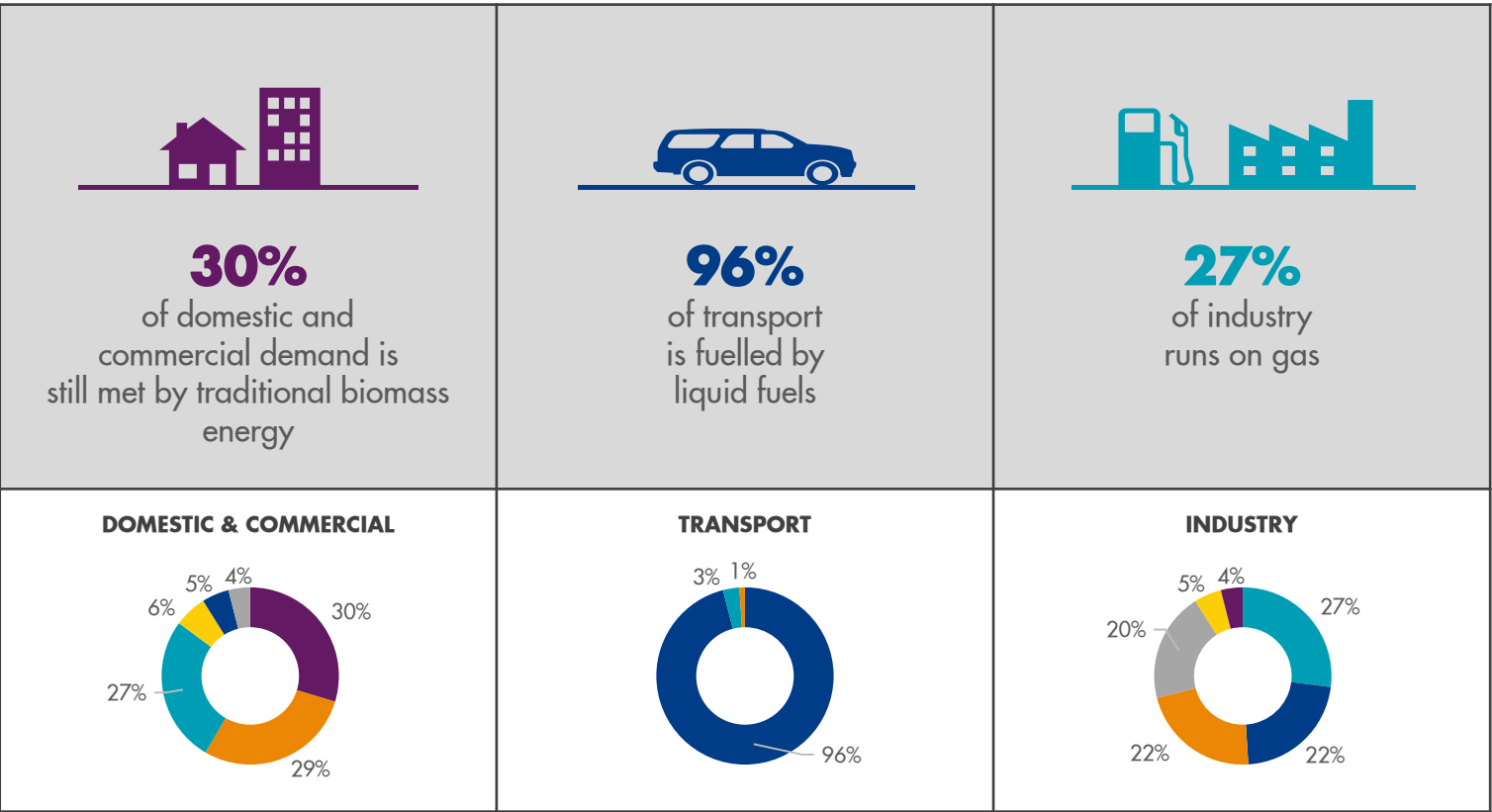


Today's Energy Mix

Current Global Energy Demand



Energy Consumption by Sector and Consumer Trends



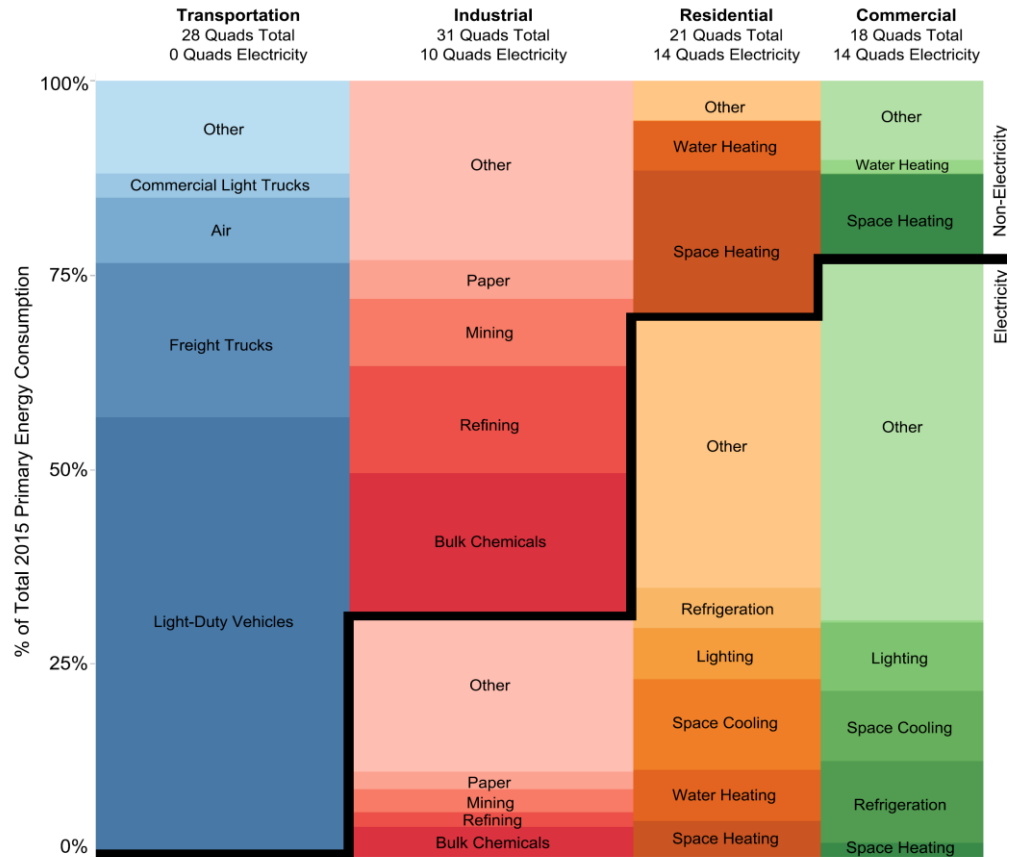
Oil Coal Gas Biomass Nuclear Renewables (including hydro) Electricity Heat Liquid fuels (including biofuels)

Source: International Energy Agency, World Energy Outlook

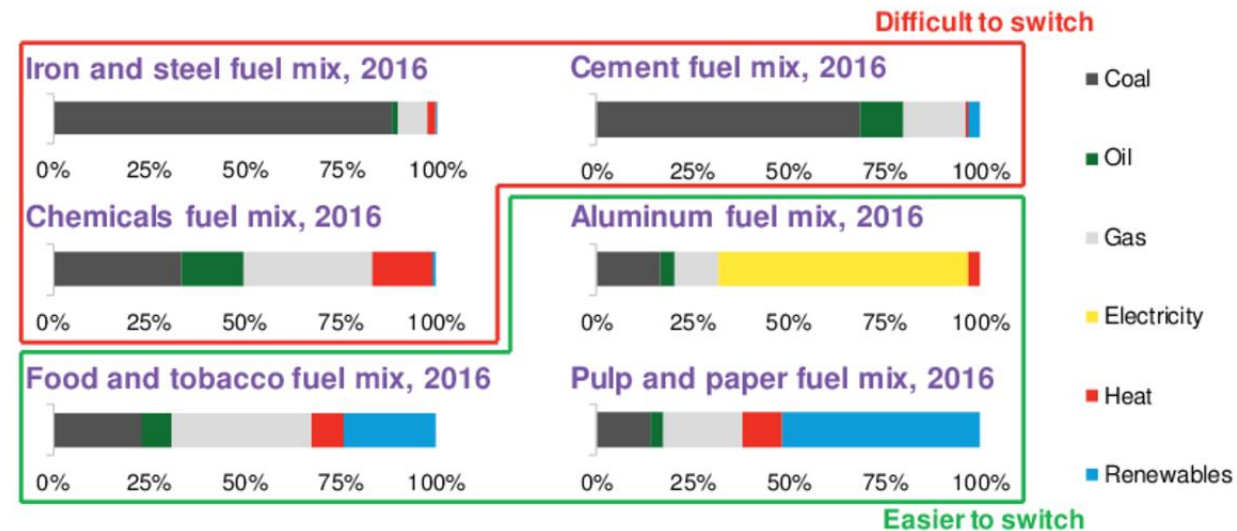
Electrification lags in transportation & industry

Sector diversity requires multiple technology options to increase electrification

US energy use by sector



Global fuel mix – industrial sector



Source: IEA Energy Balances, BloombergNEF

Electricity in the industrial sector

■ 1892

Chlor Alkali

■ 1888

Aluminum

■ 1902

Air separation



Hydrogen

Base Chemicals

Specialty
Chemicals

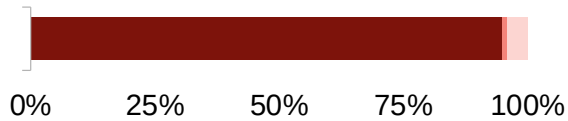
What will this require?

Process heating needs for industrial applications

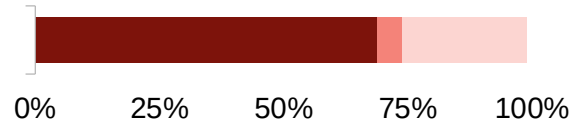
Electrifying heat could be a significant lever

Heat requirements by sub-sector

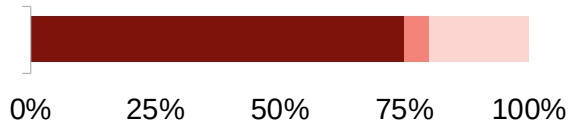
Iron and steel fuel mix, 2016



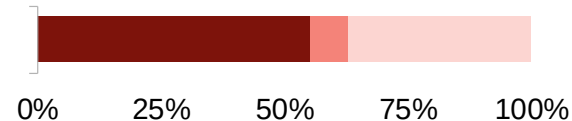
Cement fuel mix, 2016



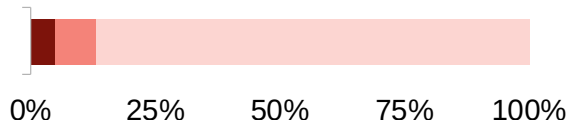
Chemicals fuel mix, 2016



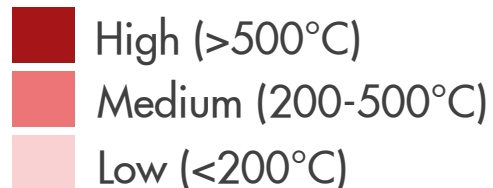
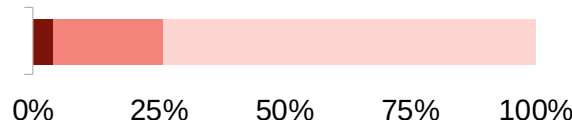
Aluminum fuel mix, 2016



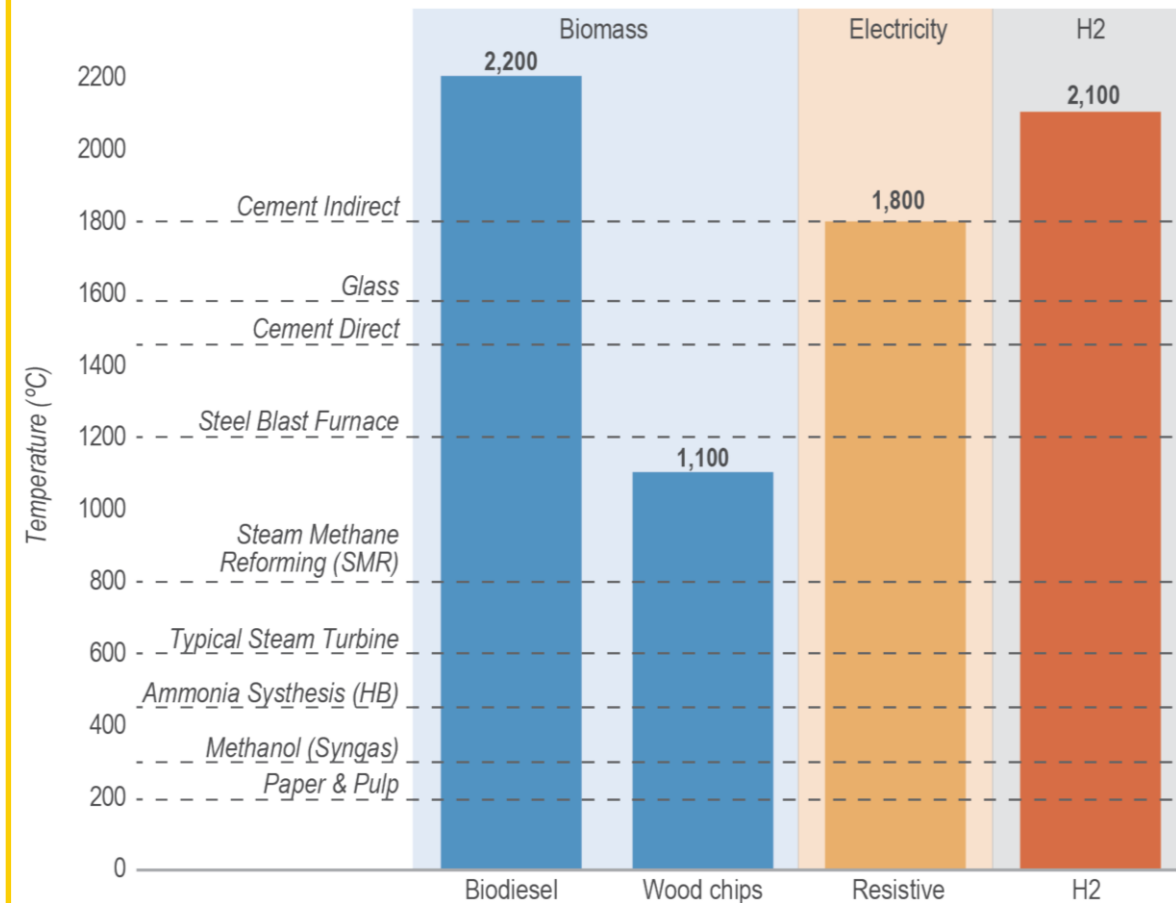
Food and tobacco fuel mix, 2016



Pulp and paper fuel mix, 2016



Temperature requirements by process



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



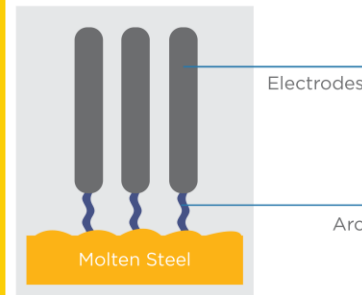
Increased efficiency in biomass transformation

Bioenergy and bio-feedstocks from lignocellulosic sources and algae

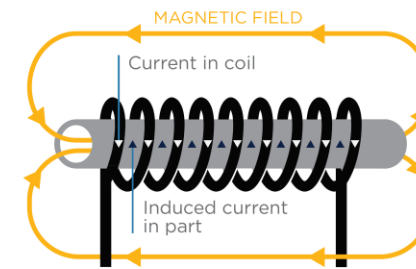
Synthetic chemistry, including direct air capture of CO₂

Potential technologies being evaluated

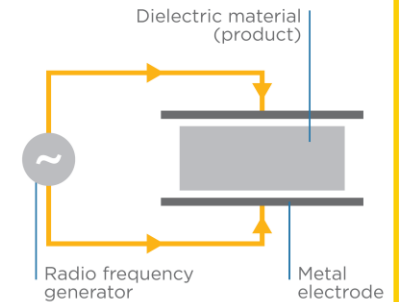
ELECTRIC ARC HEATING



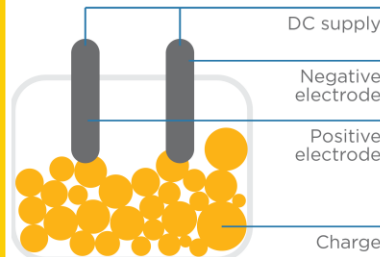
INDUCTION HEATING



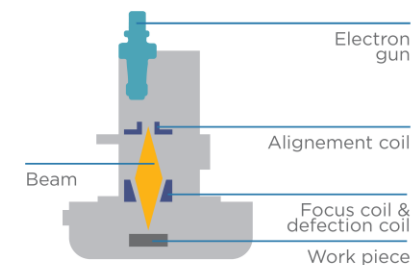
DIELECTRIC HEATING



DIRECT RESISTANCE HEATING

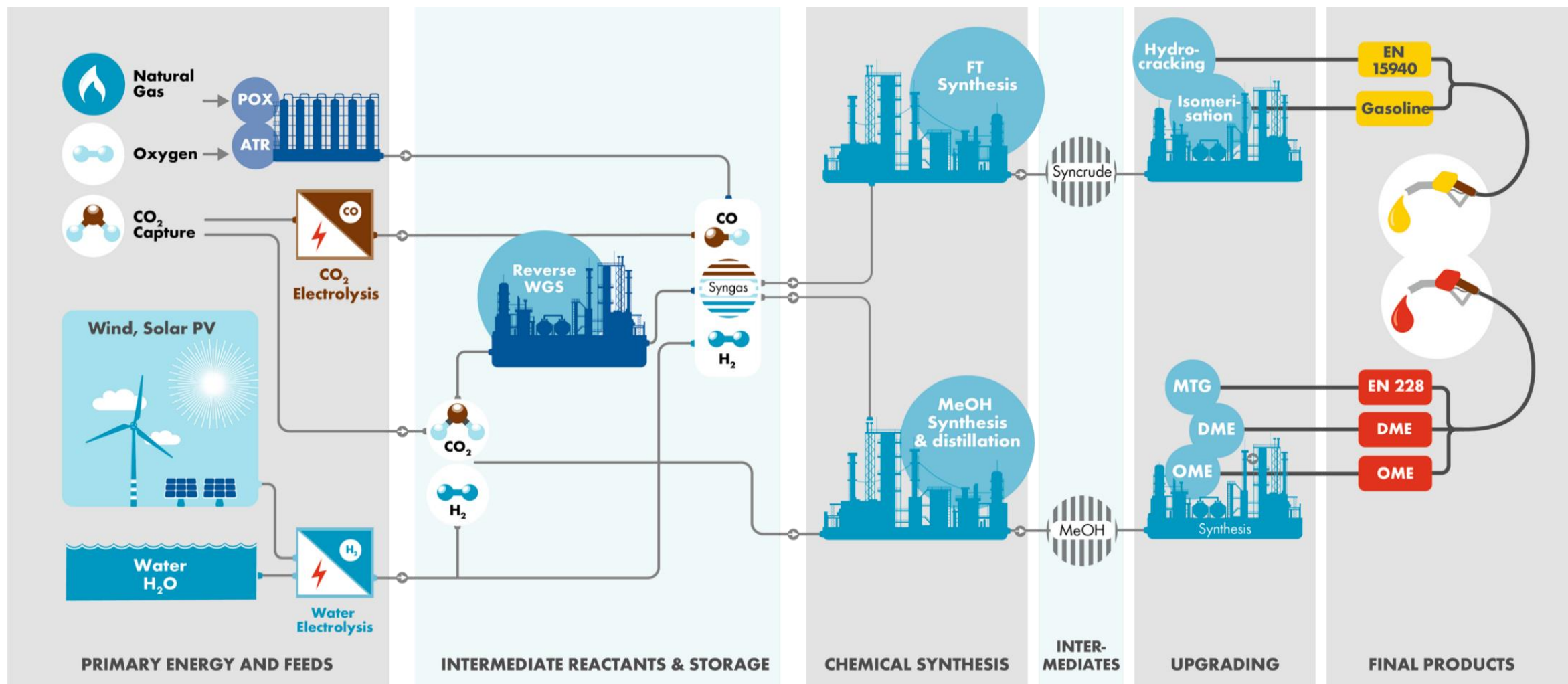


ELECTRON BEAM HEATING



Moving toward synthetic dense energy carriers

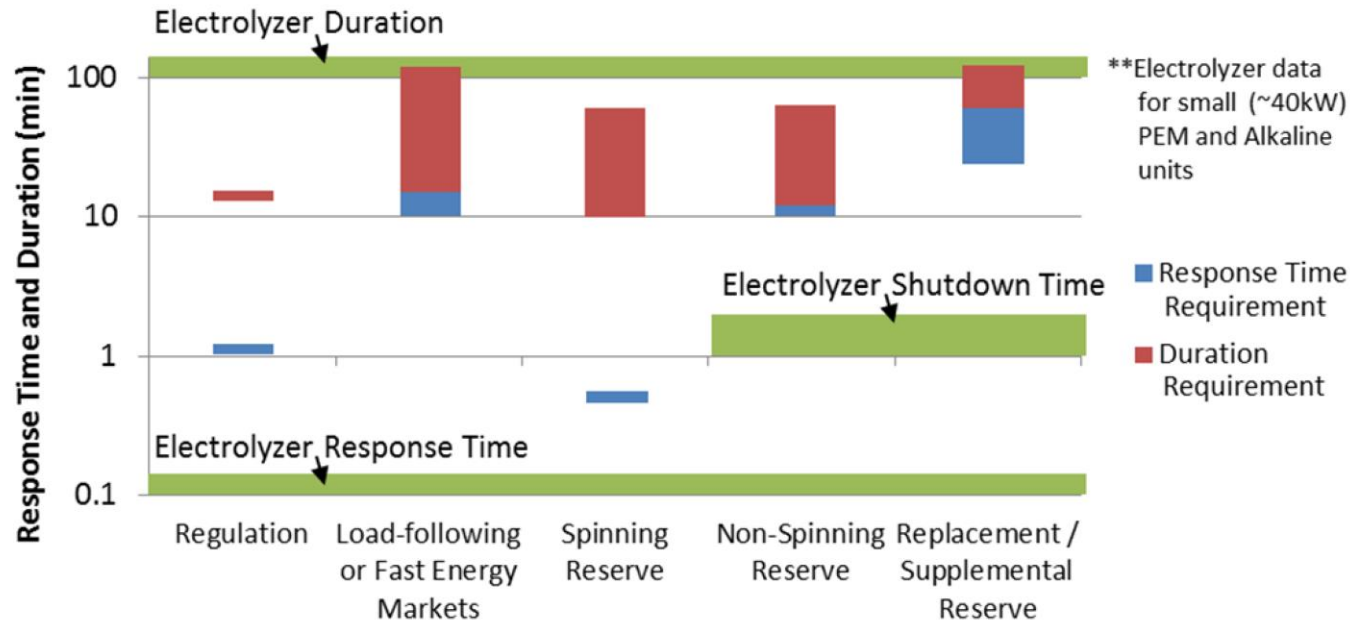
Significant role for electrified process technologies



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

Resilience in integrated systems: flexible, operable, and controllable

Concepts are similar in chemical processes & electrical systems

Computers & Chemical Engineering Vol. 7, No. 4, pp. 423-437, 1983
Printed in Great Britain.

0098-1354/83 \$3.00 + .00
Pergamon Press Ltd.

FLEXIBILITY AND RESILIENCY OF PROCESS SYSTEMS

Manfred Morari

Chemical Engineering
University of Wisconsin
Madison, WI 53706 USA

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

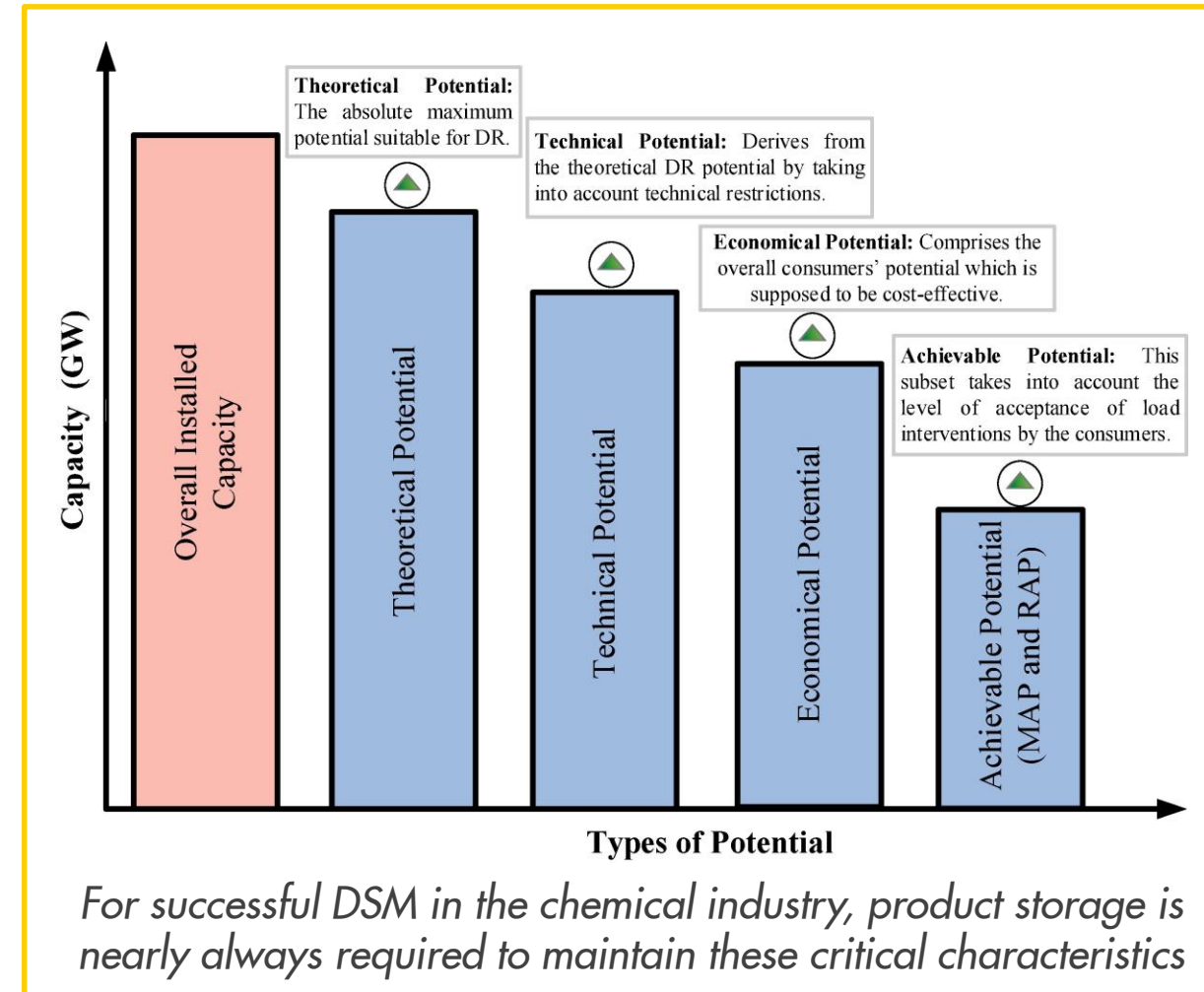
Ignacio E. Grossmann*, Bruno A. Calfa, Pablo Garcia-Herreros
Department of Chemical Engineering, Carnegie Mellon University,
Pittsburgh, PA 15123, United States

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



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 	Ammonia 	Synfuels 
Industry	Cement	Electrification of kiln heat (process emissions remain)	As heat source		
	Steel	Electrification of furnace heat Direct iron electrolysis	As reduction agent and heat source		
	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)		
	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	
	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)

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.

